# **Neutrinos: an open window on Fundamental physics** and the **Evolution** of the **Universe**

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HCPSS
Fermilab - USA

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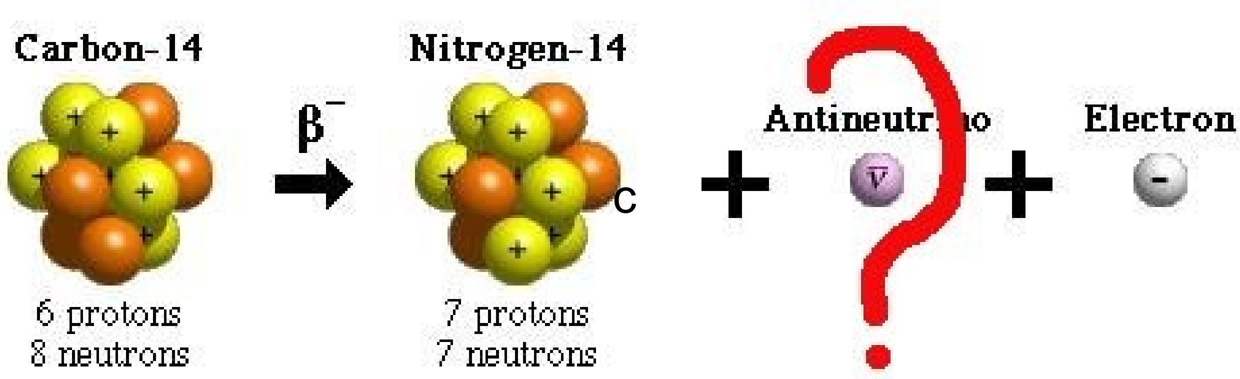
# Outline

1. The Pioneering Age of Neutrino Physics (1930 - 1997)
2. The Golden Age (1998 - 2006)
3. The Precision Era (2006 - ): a wide exp programme
4. Neutrino Physics and Larger Questions
   a) Open window on physics beyond the Standard Model
   b) Neutrinos as messengers from Early Universe
5. Conclusions

# The **Pioneering Age** of Neutrino Physics:

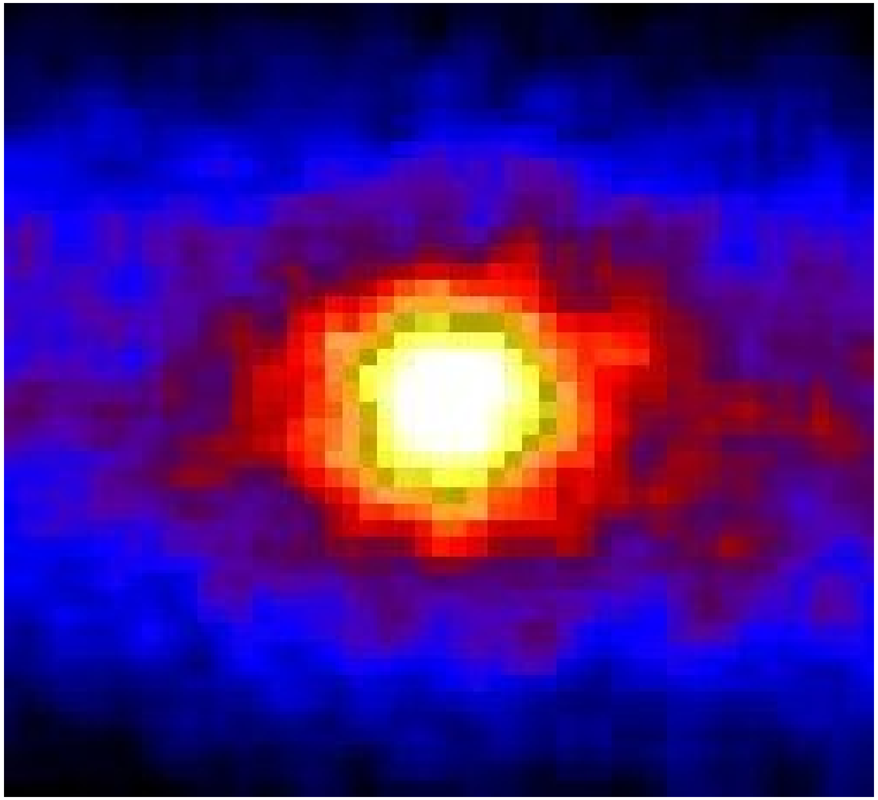
Neutrino hypothesis and its discovery (1930 – 1997)



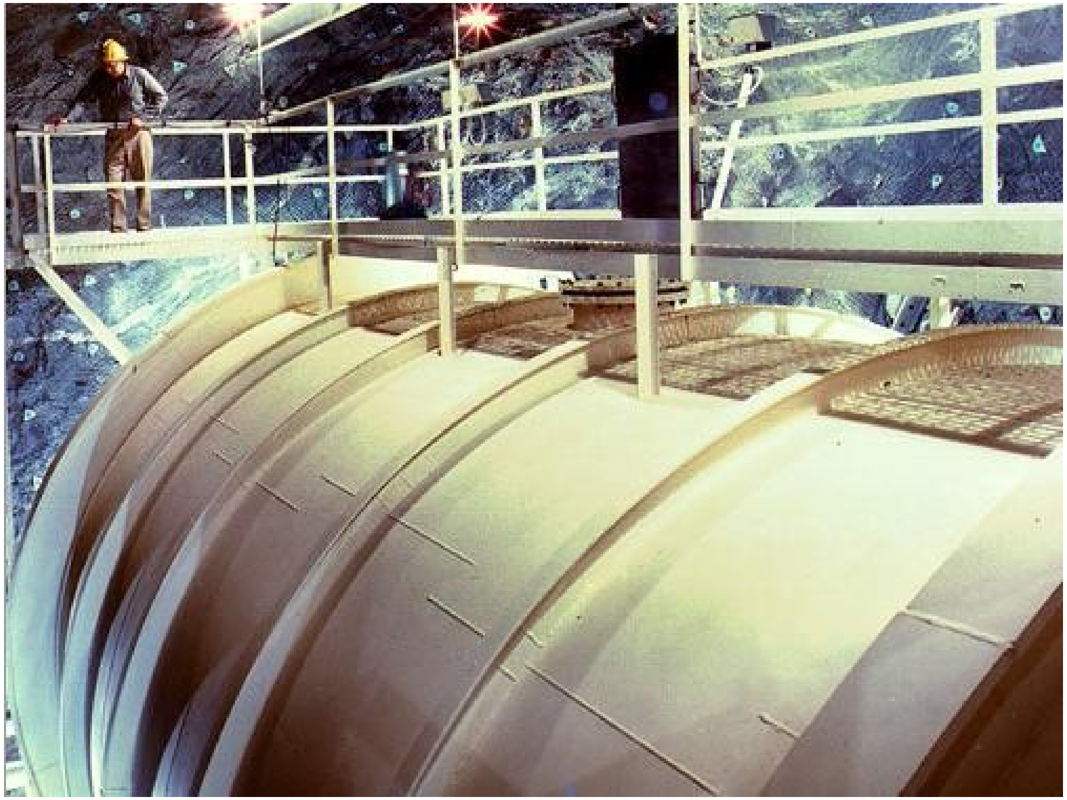

In order to explain the continuous spectrum of energy in beta decay, Pauli proposed the existence of **a very light, weakly interacting particle**: the neutron.

Fermi renamed Pauli's particle to distinguish it from the newly discovered heavy neutron: the **neutrino** (“il piccolo neutro”).

After their discovery by Cowan and Reines in 1956, searches were performed for **astrophysical neutrinos**, produced in the Sun and in the atmosphere.



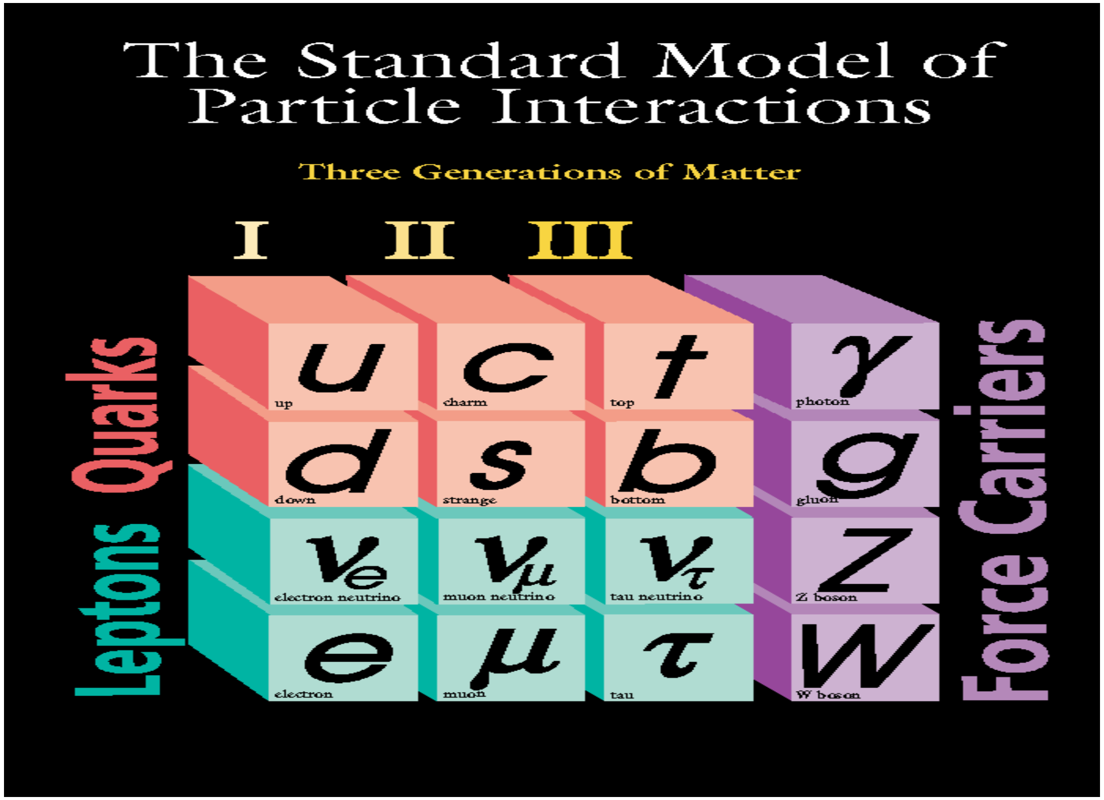
The Sun shining in neutrinos.



The Homestake experiment.

The first atmospheric neutrinos were observed in 1965 by the Kolar Gold Field (KGF) and Reines' experiments.

# The Standard Model and Neutrinos

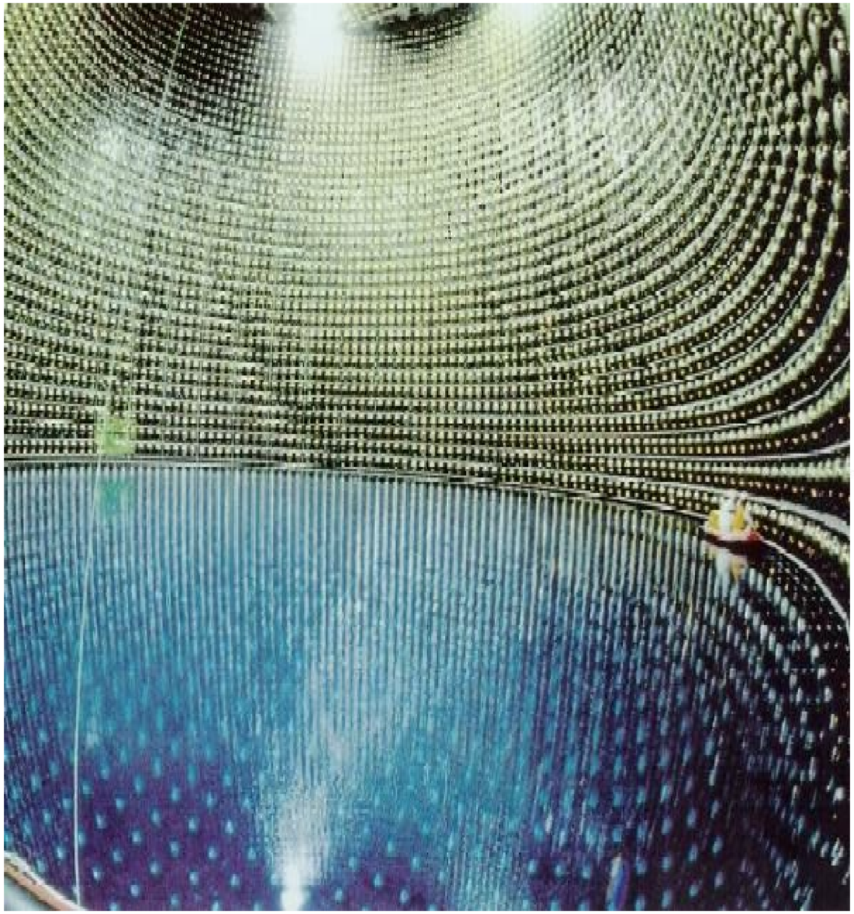



The Standard Model describes the particle which exist in Nature (fermions and bosons) and explains their interactions (strong and electroweak forces) and their masses. The missing ingredient is the Higgs boson.

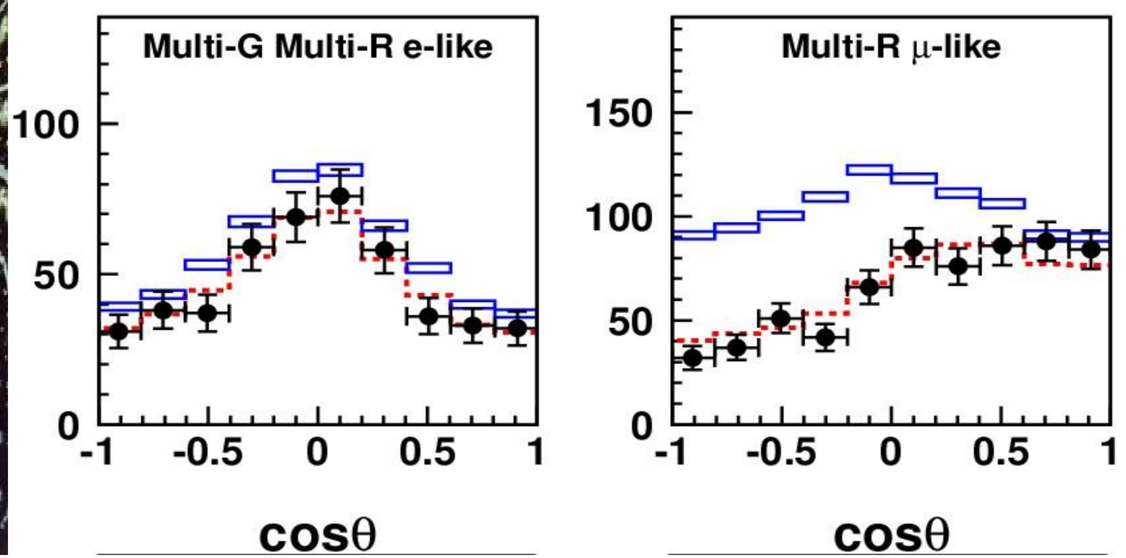
Neutrinos in the SM are left-handed and massless.

# The **Golden Age** of Neutrino Physics:

Evidence of neutrino oscillations (1998-2006)

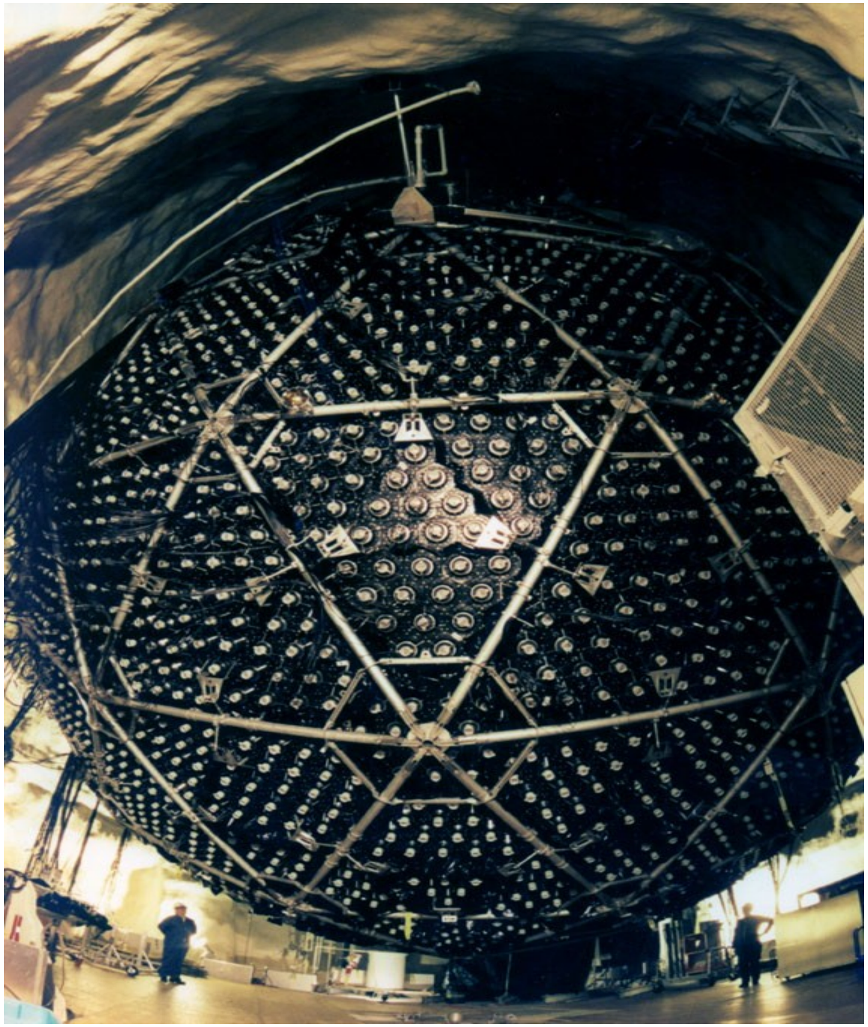


Super-Kamiokande observed a depletion of $\mu$-like events for neutrinos which transverse the Earth.



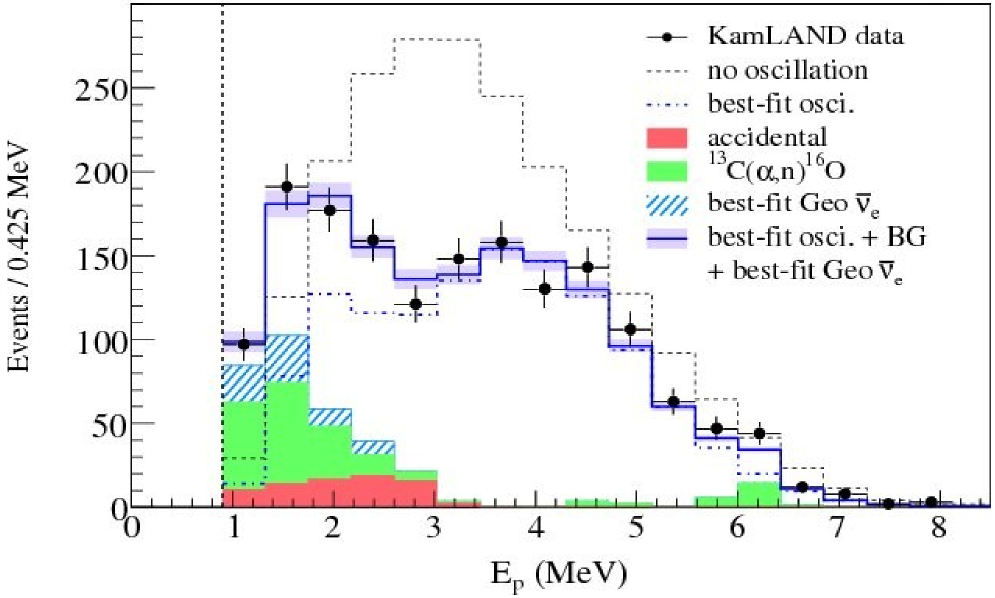

The Super-Kamiokande detector

In 2002, the SNO results confirmed the hypothesis of neutrino oscillations for solar neutrinos observing not only electron neutrino **disappearance** but also active neutrino **appearance**.



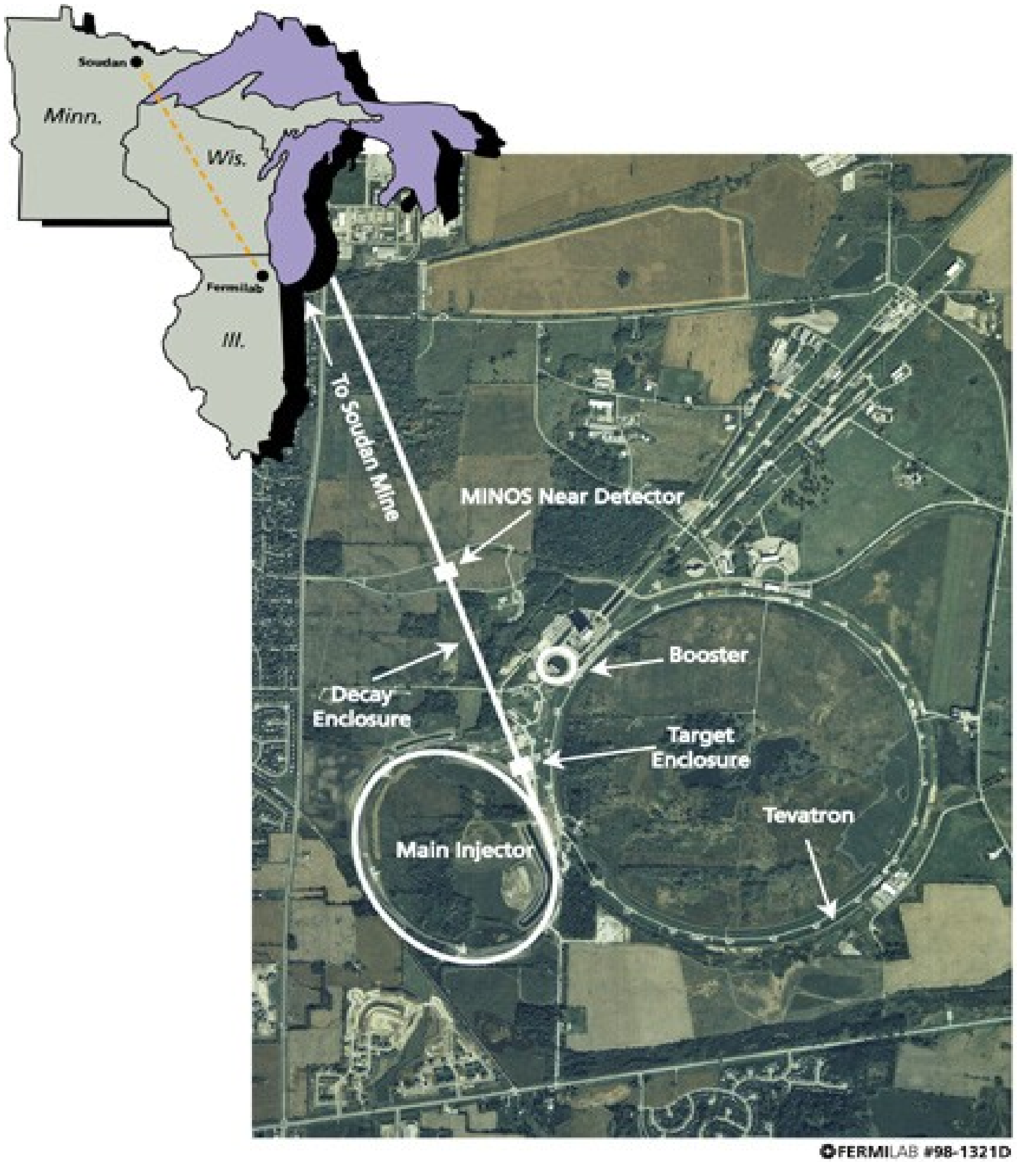
The SNO Detector

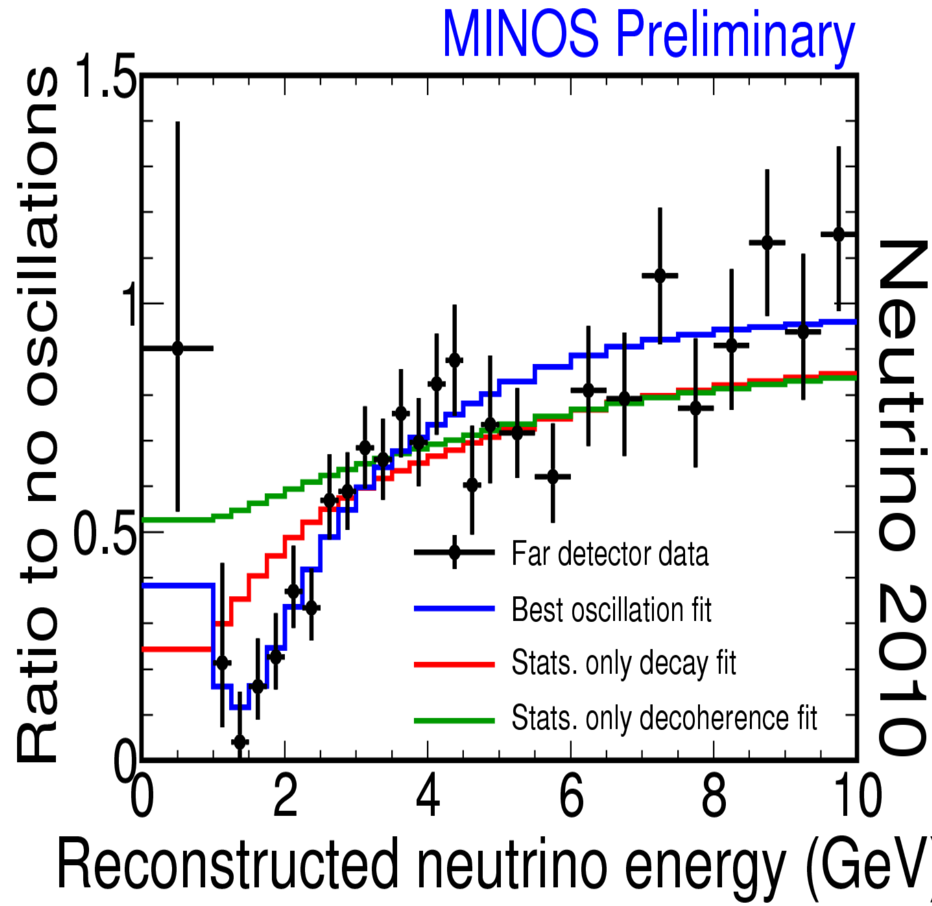
The KamLAND experiment observed the **disappearance** of reactor electron anti-neutrinos.




KamLAND events (2008)

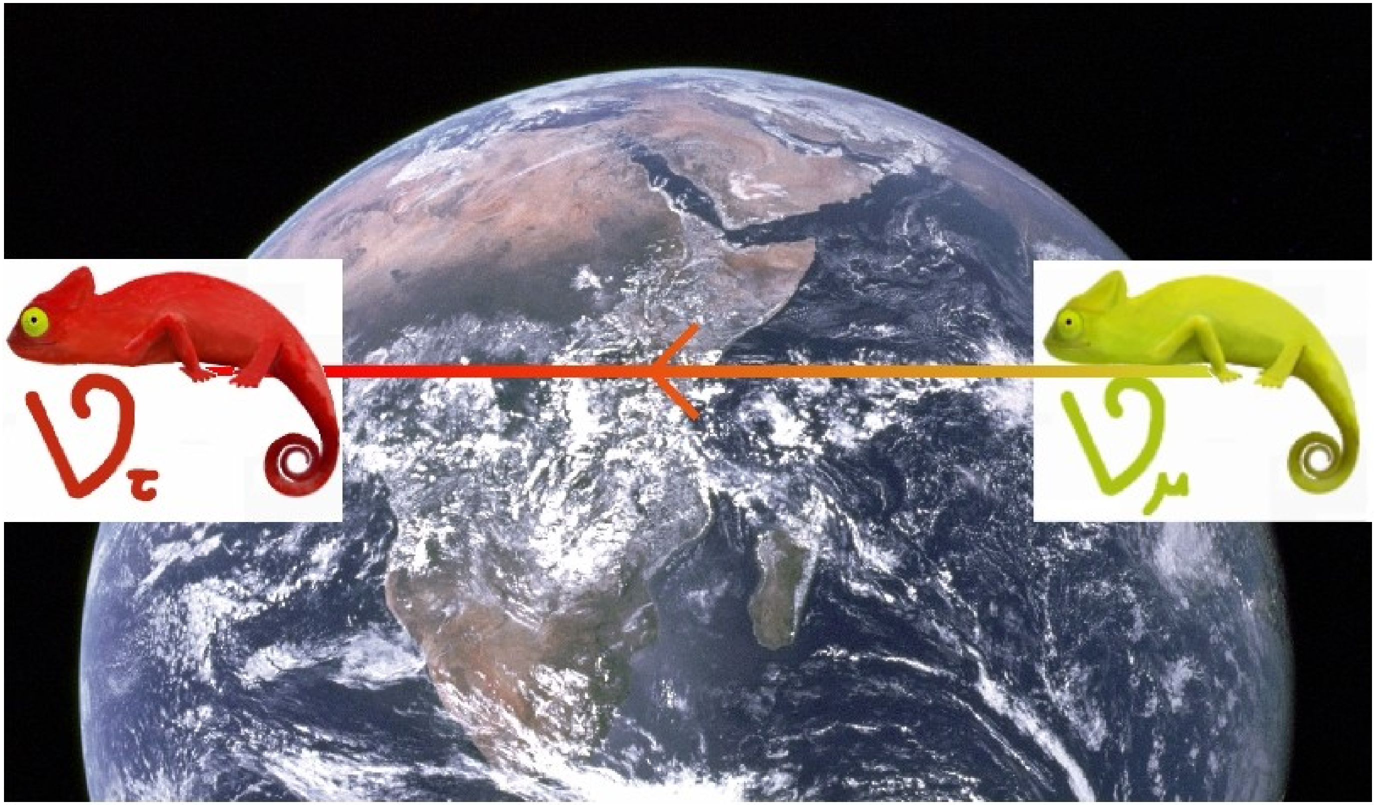
**Accelerator neutrinos** (MINOS; also K2K and OPERA, ICARUS) search for neutrino oscillations.




MINOS: A beam of muon neutrinos is produced at Fermilab and detected 735 km away, confirming atmospheric neutrino oscillations.

## Neutrino oscillations: neutrinos are chameleon particles




In a SM interaction a **neutrino of one type (electron, muon or tau)** is produced. While travelling it **changes its "flavour"** and can become a different **neutrino (muon into tau)**.

Due to **mixing**, two neutrino basis: **Flavour and Massive** basis

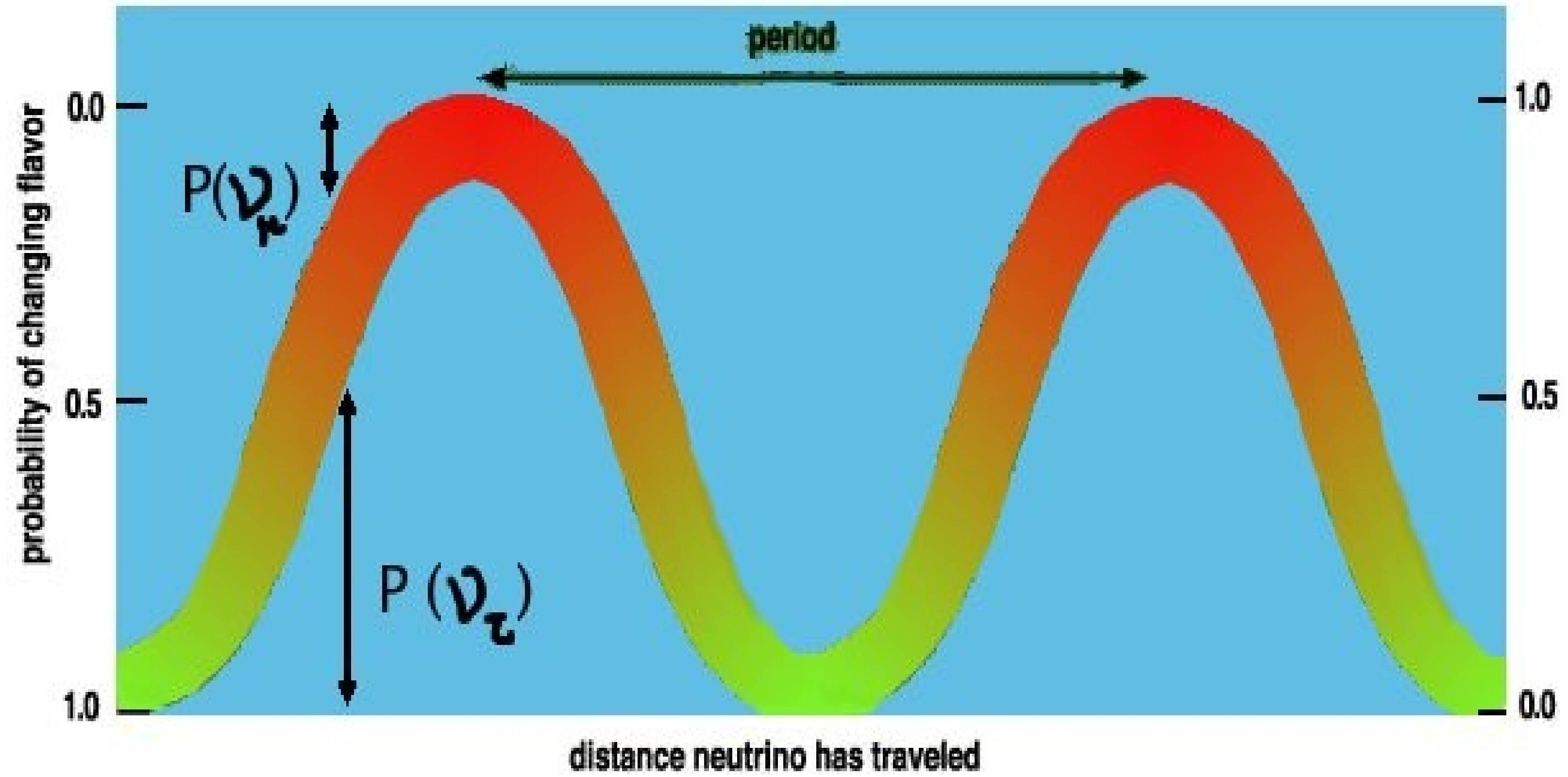
$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

At t=0 a muon neutrino is produced. At a later t:

$$|\nu, t\rangle = e^{-i\mathcal{H}t}|\nu, 0\rangle = e^{-iE_1 t}\left(-\sin\theta|\nu_1\rangle + e^{-i(E_2-E_1)t}\cos\theta|\nu_2\rangle\right)$$

As neutrinos are highly relativistic, $E_2 - E_1 \simeq (p + \frac{m_2^2}{2E}) - (p + \frac{m_1^2}{2E}) \simeq \frac{\Delta m^2}{2E}$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2 \frac{\Delta m_{21}^2 L}{4E}$$

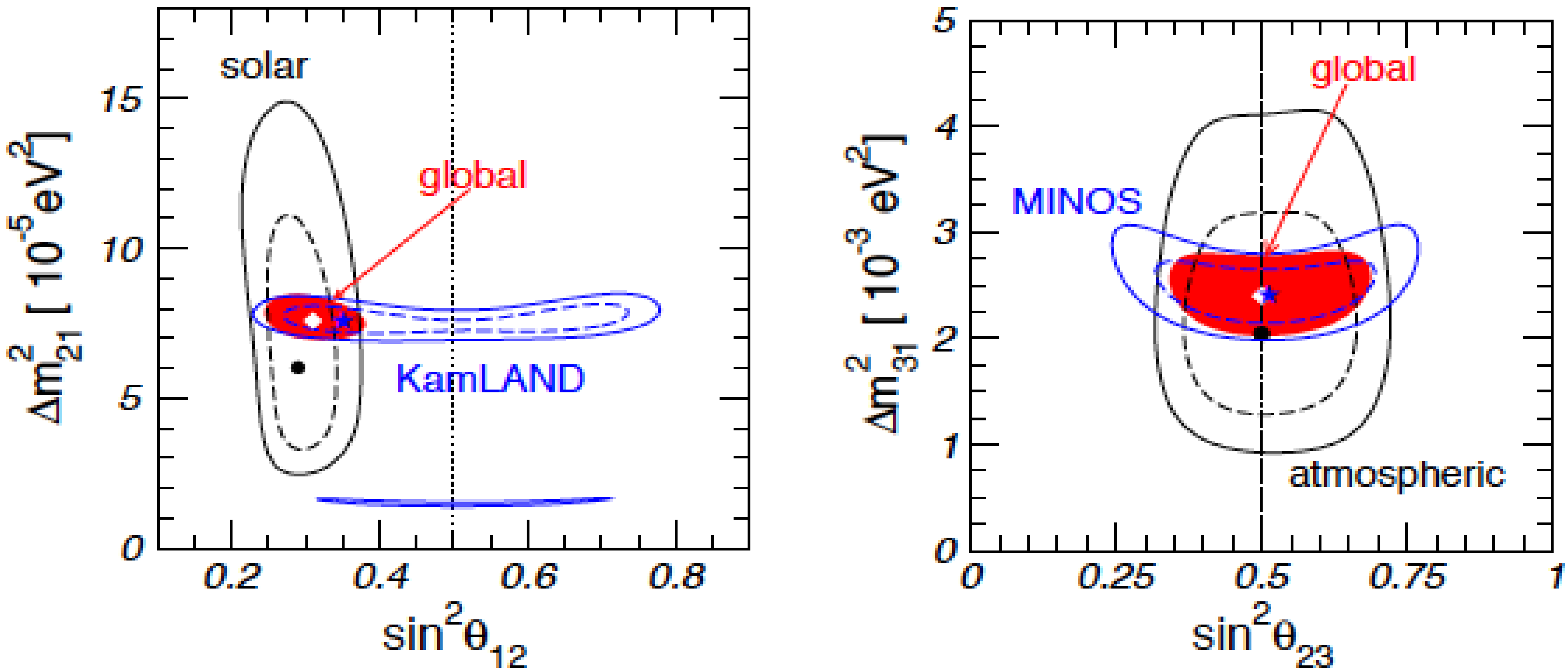



**Neutrino oscillations imply that neutrinos have mass and they mix!**

**First evidence of physics beyond the Standard Model.**

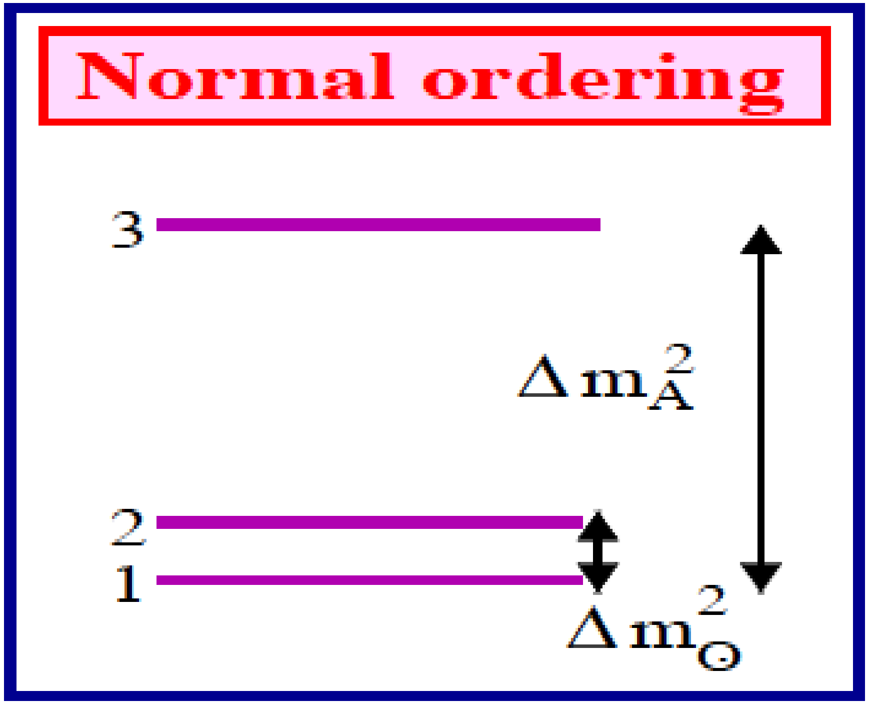
# Present knowledge of neutrino parameters

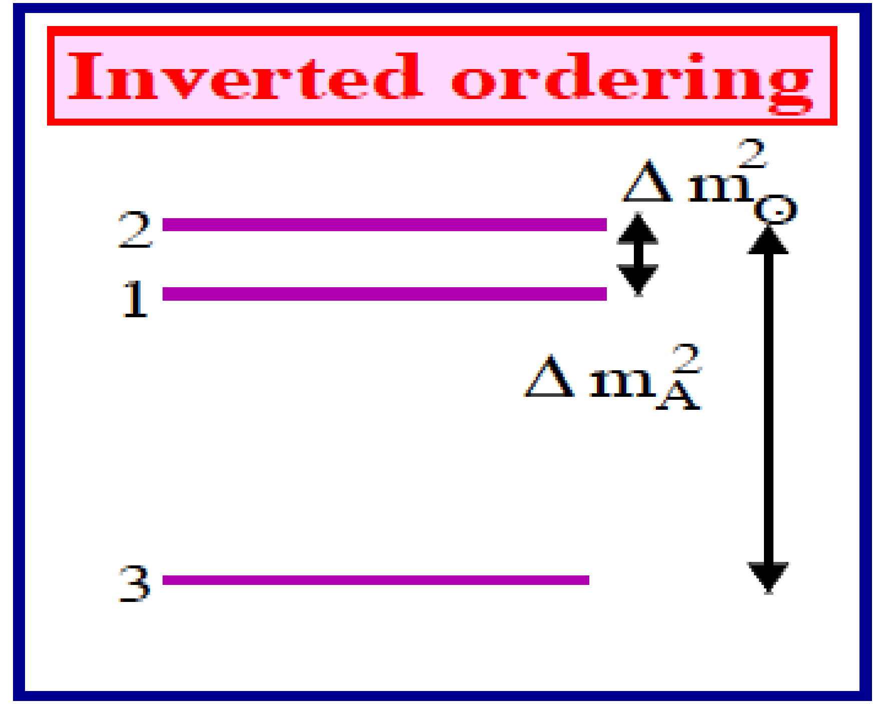
Neutrino oscillations measure mass squared differences and mixing angles.




Maltoni, Schwetz, 0812.3161

$\Delta m^2_{\odot} \ll \Delta m^2_{\mathrm{A}}$ implies at least 3 neutrino mixing.

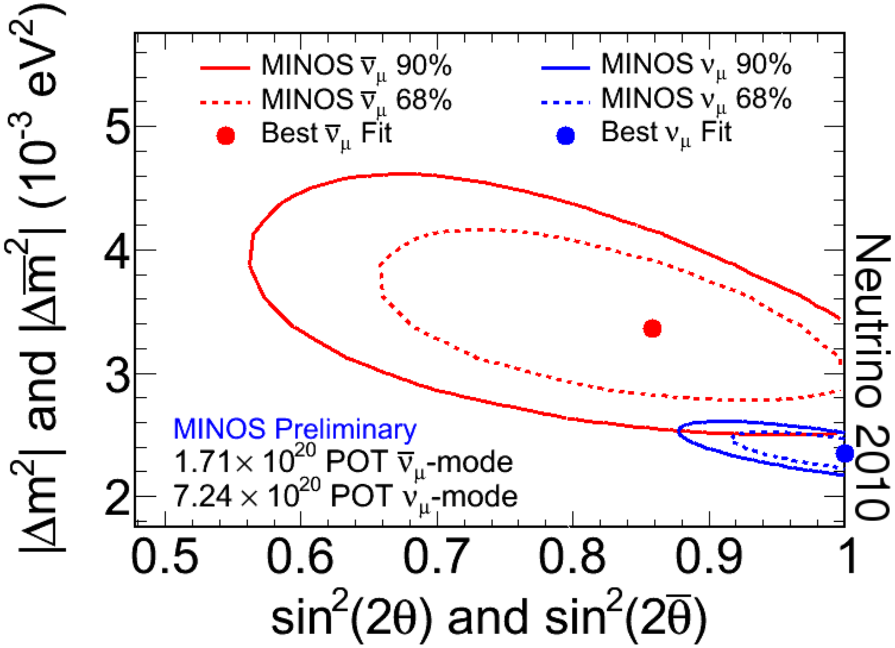



- Neutrino masses are **much smaller than other fermion masses**.

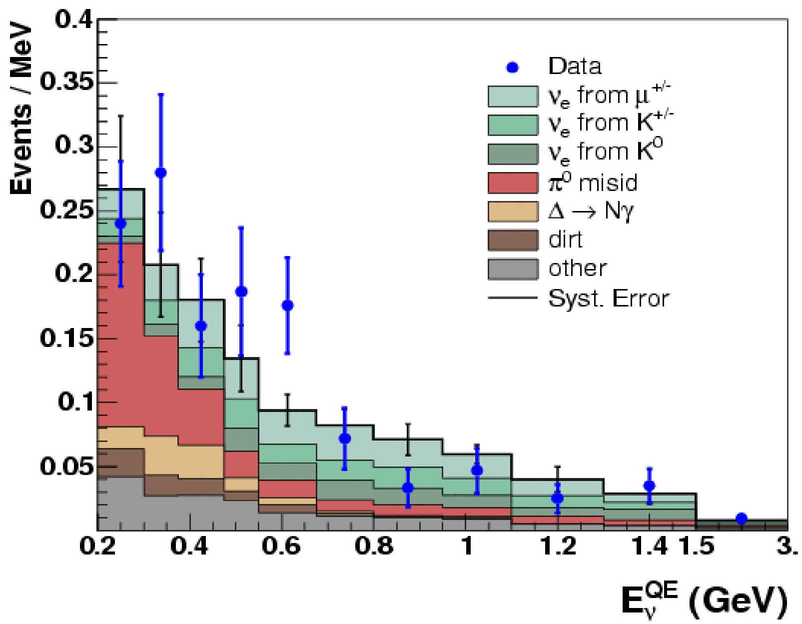
- Mixing is described by a unitary 3x3 matrix **U**, which contains 3 **angles** and can be complex due to phases (**CP-violation: neutrinos and antineutrinos behave differently**).

# Is the 3-neutrino standard picture correct?




**MINOS** reported different oscillations for neutrinos and antineutrinos.
Is it due to Non-Standard interactions of neutrinos with matter?

MiniBooNE, PRL 103




**LSND** and **MiniBooNE** have reported the appearance of electron neutrinos at short distance, not found by other experiments.
Is it the indication of new physics?

We need new experiments to check the results with better precision.

# The **Precision Era** of Neutrinos:

## Hunting for neutrino masses, mixing and their origin (2006-)

With the discovery of neutrino oscillations, a **new perspective** has opened on neutrino physics with compelling questions which await their answer:

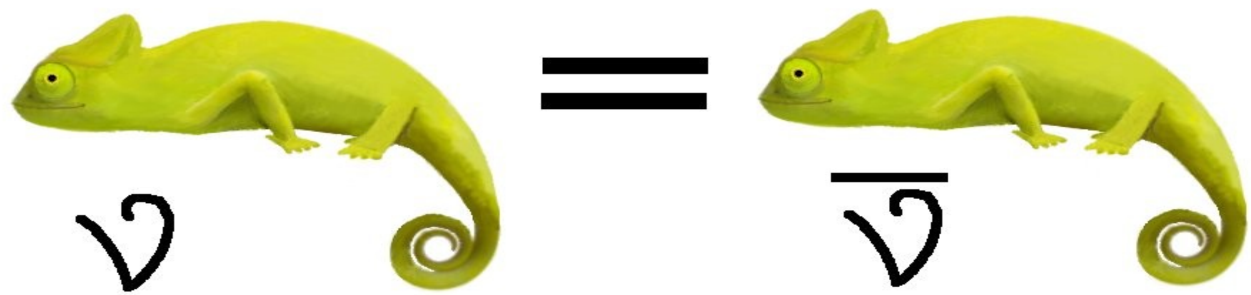
1. **What is the nature of neutrinos?**
2. **What are the values of neutrino masses and mixing?**
3. **Is the charge/parity (CP) symmetry broken?**
4. **Are there sterile neutrinos?**

A wide experimental program is going to address these questions in the next future.

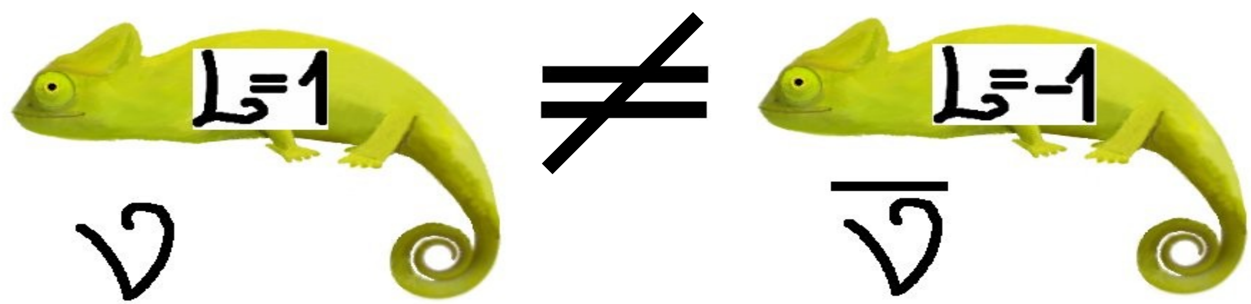
# Nature of Neutrinos: Majorana vs Dirac

Neutrinos can be **Majorana** or **Dirac** particles. In the SM only neutrinos can be Majorana because they are **neutral**.

Majorana particles are indistinguishable from antiparticles.

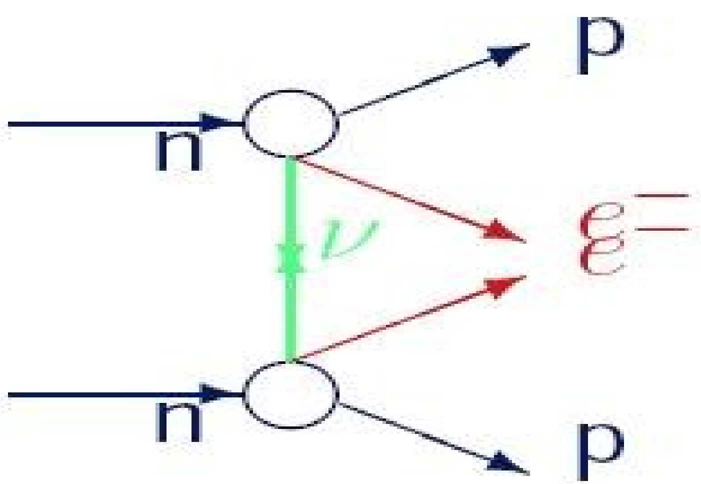



Dirac neutrinos are labelled by the lepton number.




The **nature** of neutrinos is linked to the conservation of the **Lepton number (L)**. This information is crucial in understanding the **Physics BSM**: **with or without L-conservation**?

Neutrinoless double beta decay, (A, Z) → (A, Z+2) + 2 e, will test the nature of neutrinos. It violates L by 2 units.

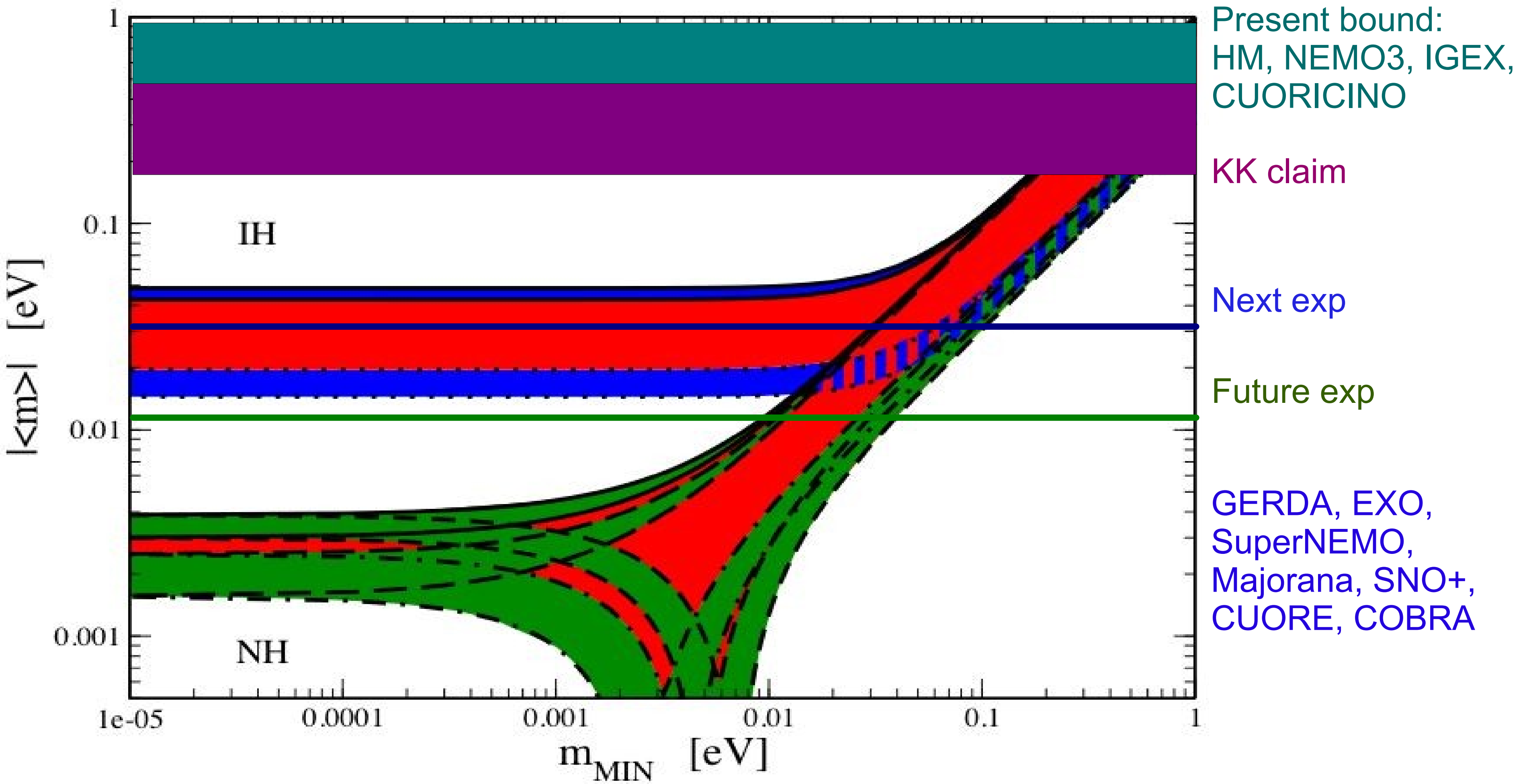



The half-life time depends on neutrino properties through

$$\boxed{|<m>| \equiv |\, m_1 |U_{e1}|^2 + m_2 |U_{e2}|^2 e^{i\alpha_{21}} + m_3 |U_{e3}|^2 e^{i\alpha_{31}} \,|\,,}$$

CPV phases (unknown)

Mixing angles (mostly known)



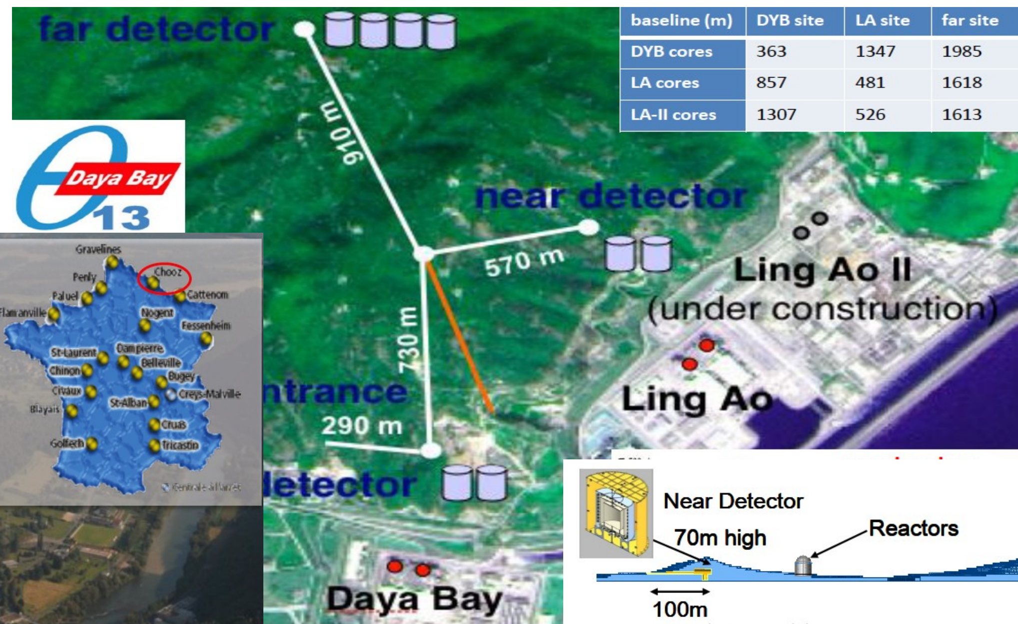

SP, S. Petcov

**Wide experimental program** for the future: **a positive signal would indicate that L is violated! This information is very important to understand what the origin of neutrino masses is.**

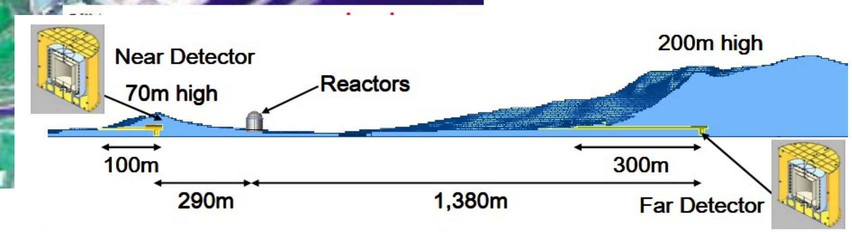
# Reactor neutrinos: the hunt for theta13

**One angle is still unknown: theta13.**

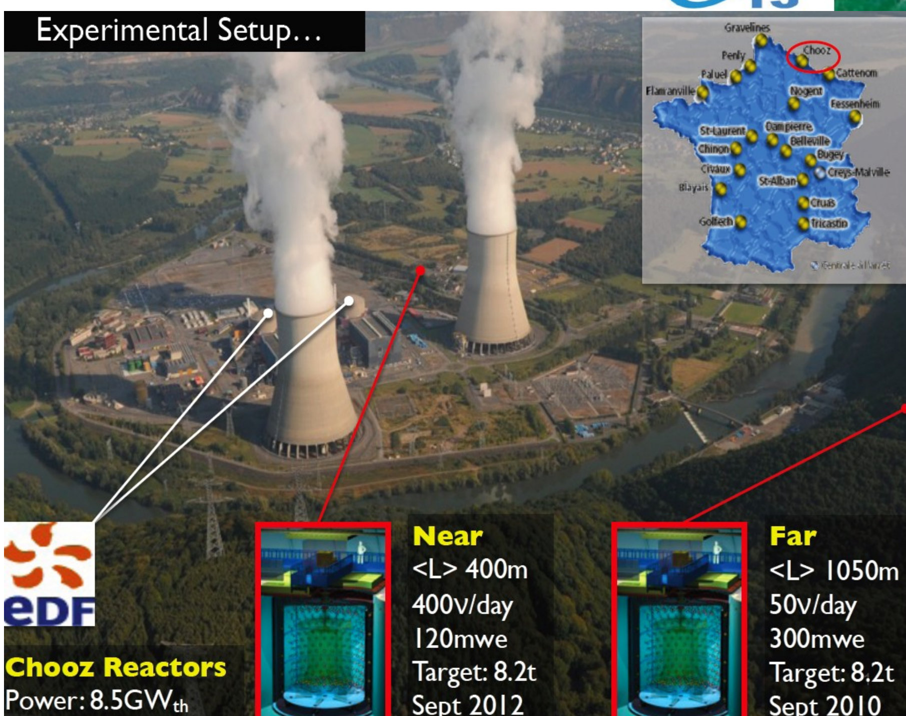
- Its value is important to understand why there is mixing.
- It opens the possibility to search for CP-violation.
- In matter neutrinos and antineutrinos would behave differently.



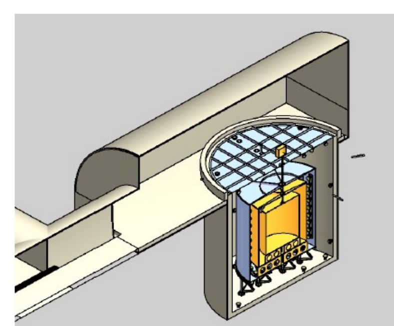

| baseline (m) | DYB site | LA site | far site |
|---|---|---|---|
| DYB cores | 363 | 1347 | 1985 |
| LA cores | 857 | 481 | 1618 |
| LA-II cores | 1307 | 526 | 1613 |




RENO
K.K. Joo



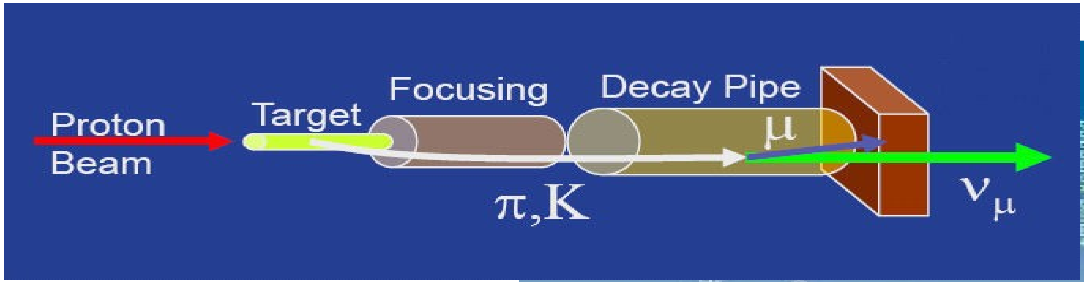

Daya Bay
M. Wang



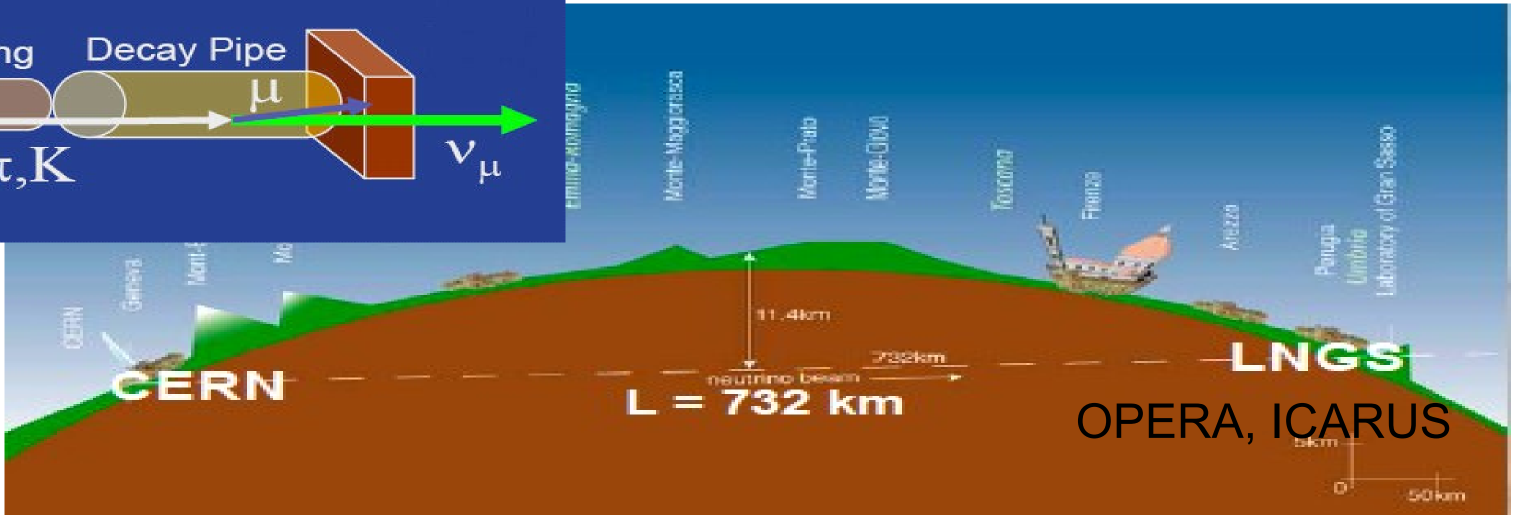
Double-CHOOZ, A. Cabrera

# Long baseline neutrino experiments

A wide program for long baseline experiments is under discussion. Neutrinos are produced in an accelerator complex and then detected 100s-1000s km away with huge detectors.




Neutrino production.
Credit: Fermilab

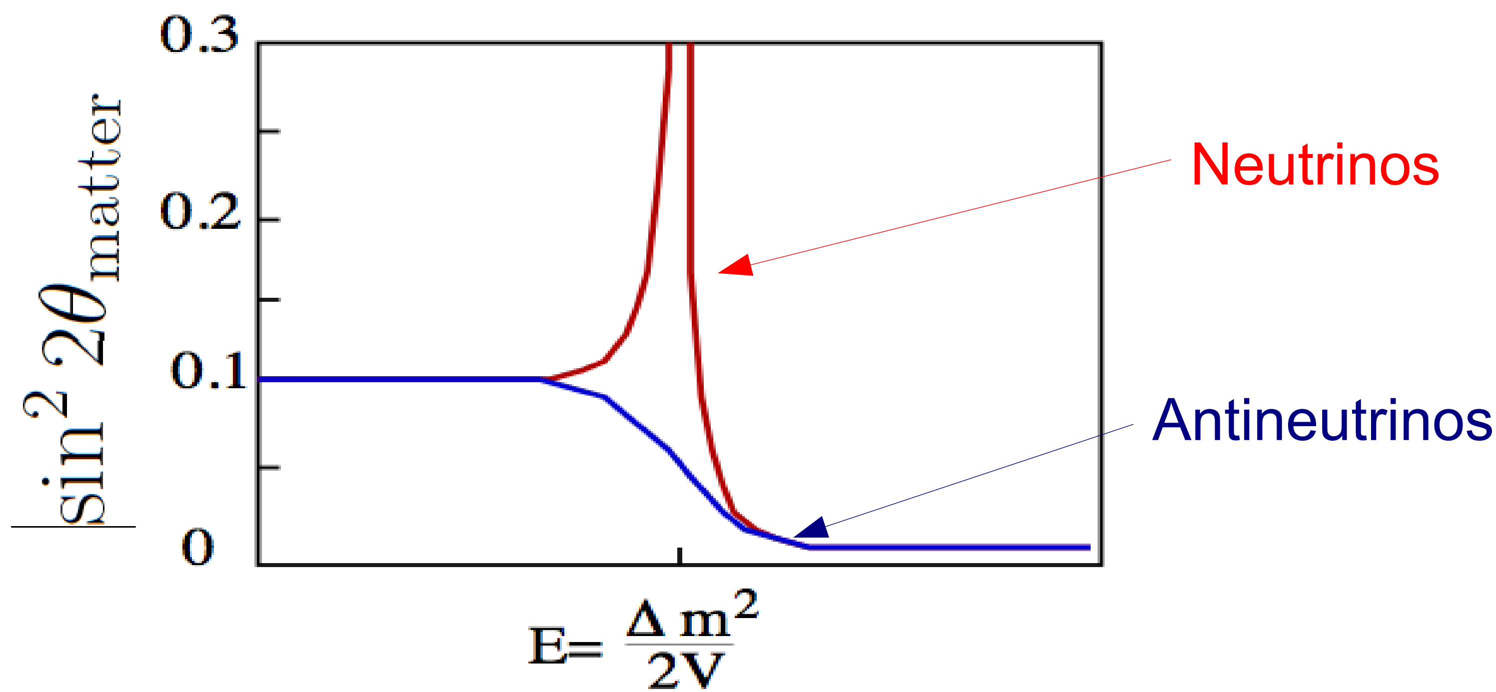



$$\boxed{P(\nu_\mu \to \nu_e) = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\frac{\Delta m^2_{31} L}{4E} + \dots}$$

These oscillations are controlled by the unknown angle $\theta_{13}$ .

• **CP-violation (U complex)**: neutrinos and antineutrinos behave differently and their **oscillation probabilities are not the same**.

• Neutrinos travel in matter and acquire an effective mass. **Matter effects are different for neutrinos and antineutrinos** because the Earth contains only electrons and no positrons: **the probability for (anti-)neutrinos is enhanced (suppressed)** or viceversa.




**Degeneracies**: in the neutrino and antineutrino oscillations, it is necessary to disentangle the CPV effects from the matter ones.

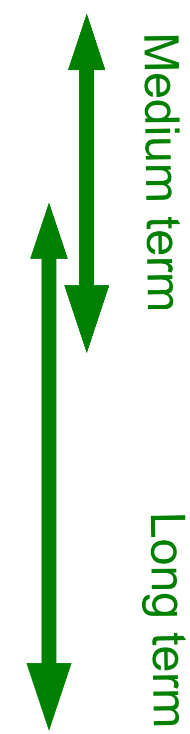
By studying the appearance and disappearance oscillation **probabilities for neutrinos and antineutrinos**, one will get information about nu **masses, mixing angles and CP-symmetry**.

A wide and very exciting **experimental program** is under intense discussion.

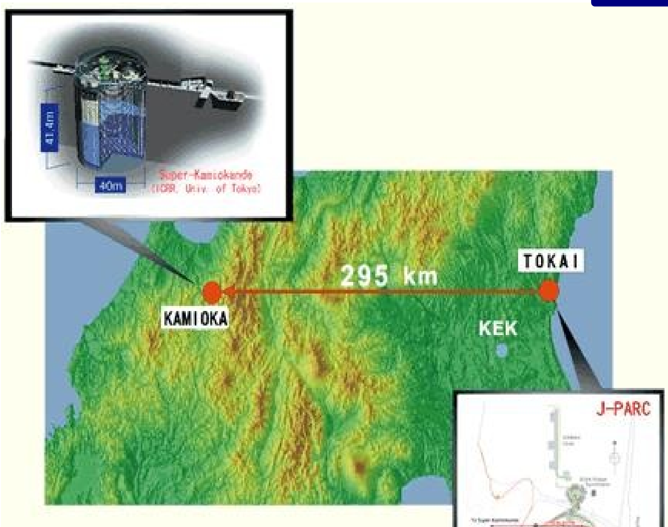
- **Superbeams**: T2K, NOvA, LBNE, SPL, LAGUNA. Use very intense muon neutrino beams from **pion decay** and search for electron neutrino appearance.

- **Betabeams**: Use electron neutrinos from high-gamma **ion decays**.

- **Neutrino factory**: Use muon and electron neutrinos from **high-gamma muon decays** and need a magnetised detector. High energy option and LENF.

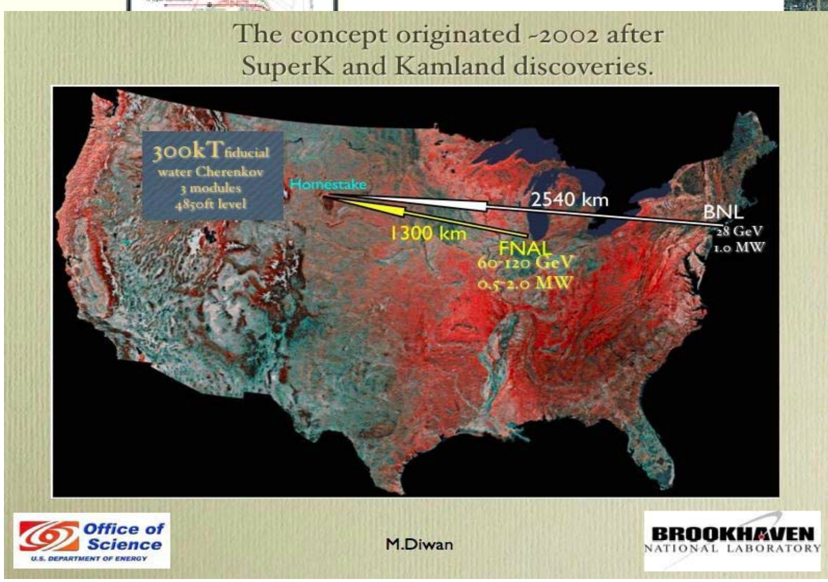


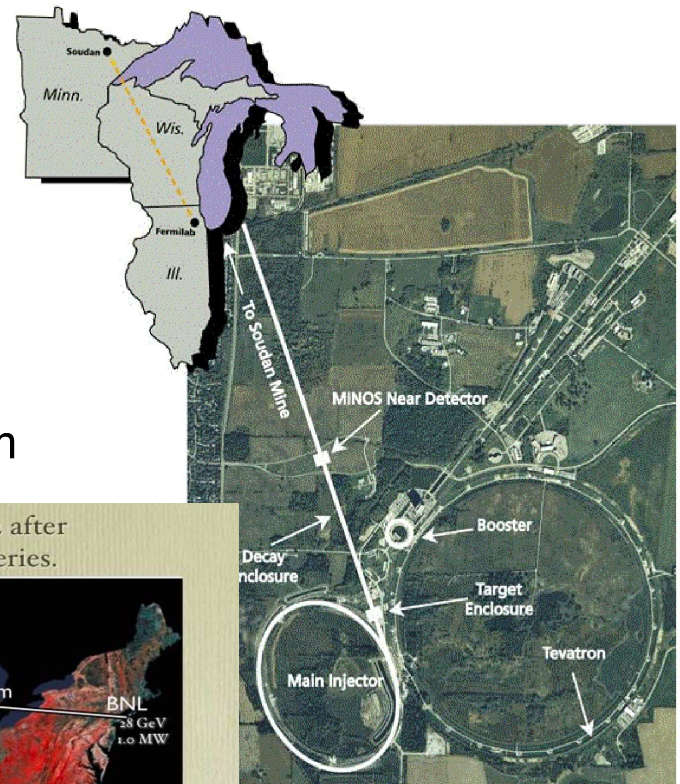
# Superbeams




T2K: off-axis
L= 295 km

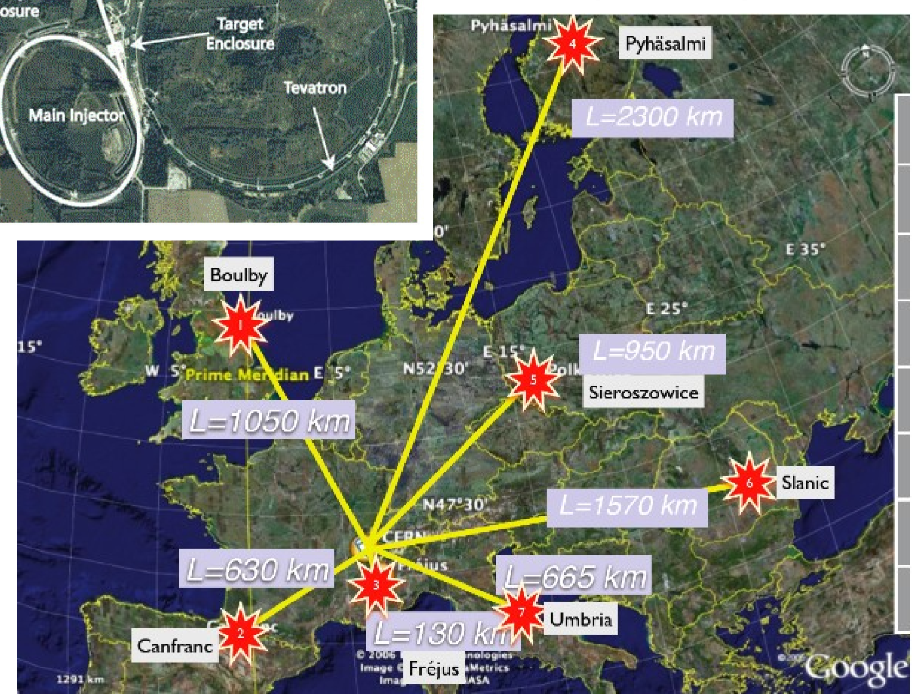
LBNE
L= 1280 km




NOvA: off-axis
L=810 km

European options




Higher precision requires longer baselines and more intense beams.

A. Rubbia


T. Kobayashi

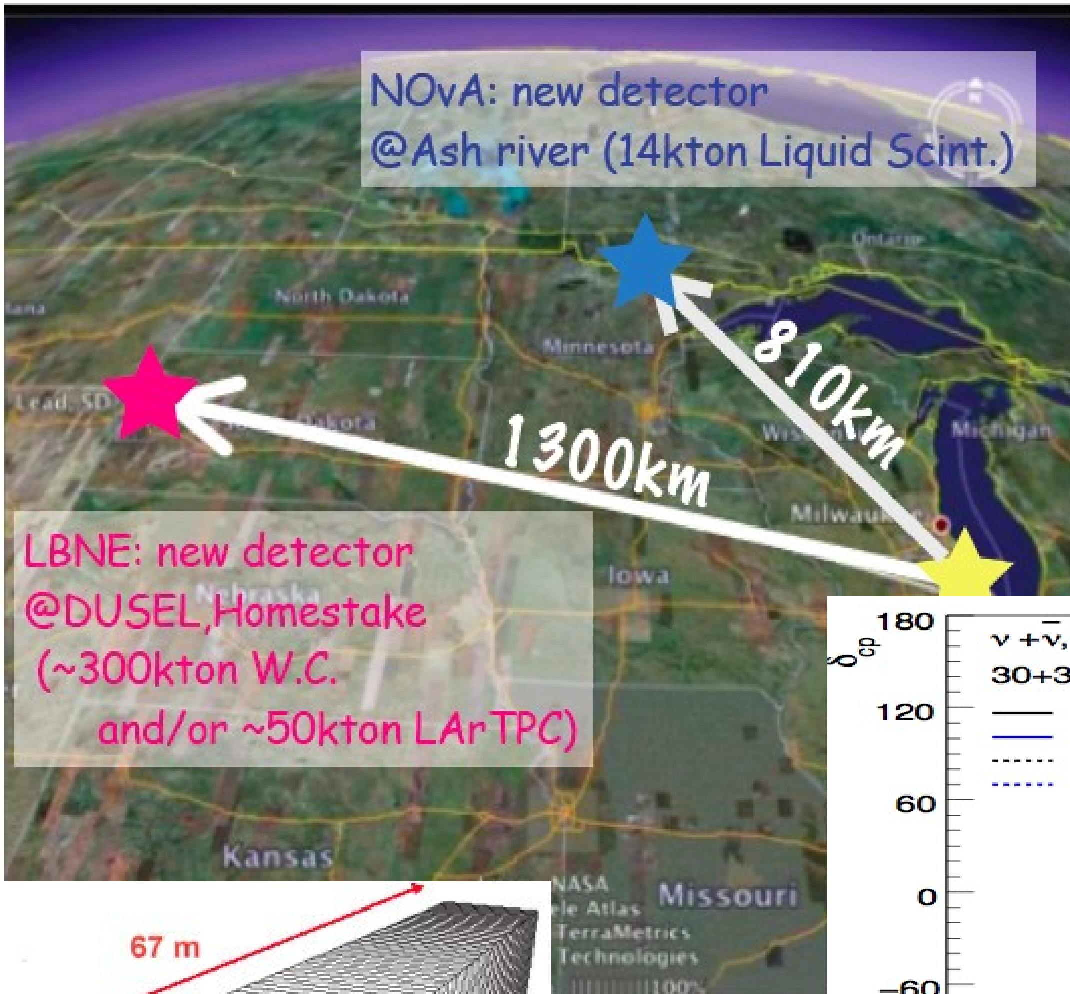
• Neutrinos are produced from accelerated pion decays. The beam travels for 295 km before being detected at Super-Kamiokande. It searches for muon to electron neutrino events.

• Goals: determine the missing angle and open the hunt for CP-violation.

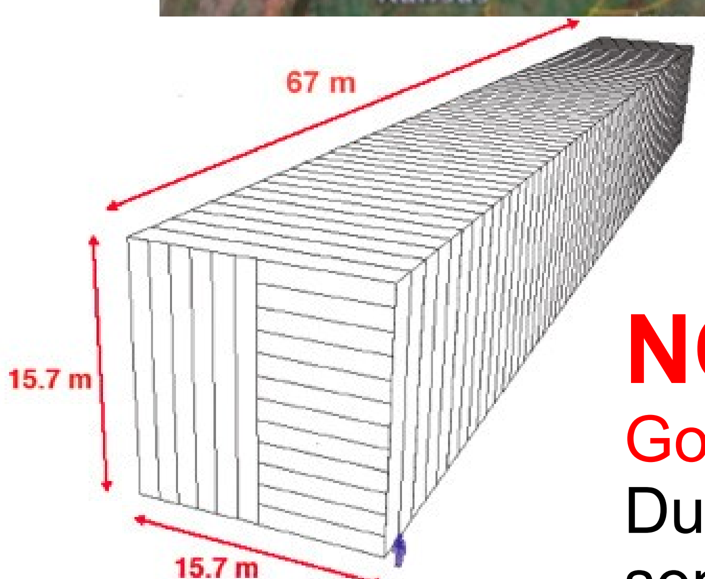
• In Feb 24 2010, the first T2K event was seen in SK!

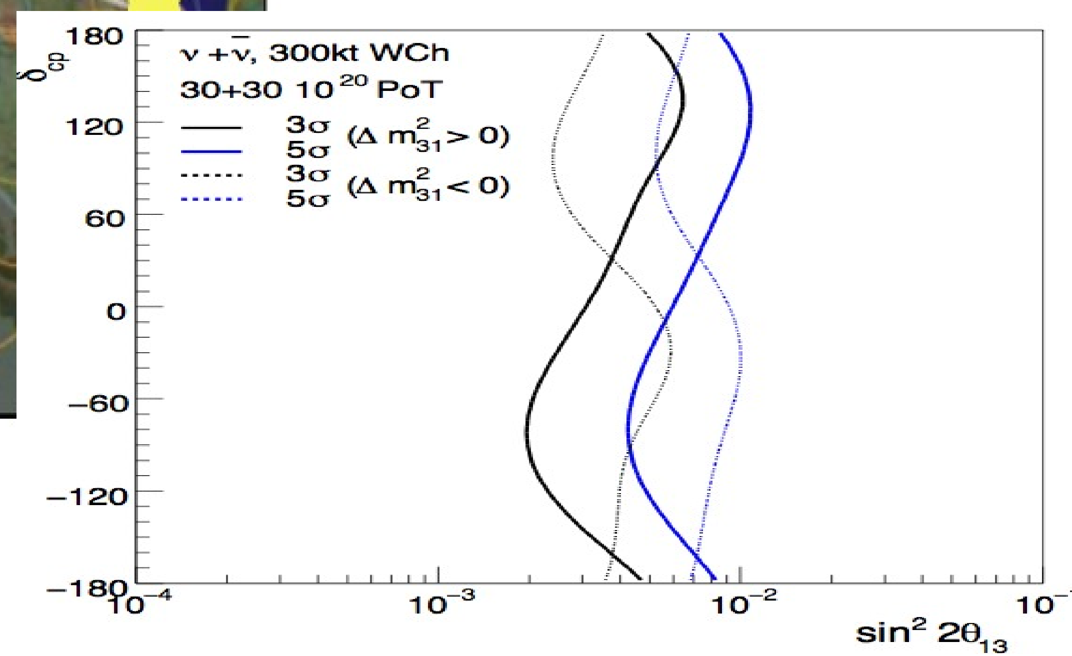
# LBNE

Goals: small theta13, CPV and matter effects, thanks to the long baseline and the large detector




K. Sakashita



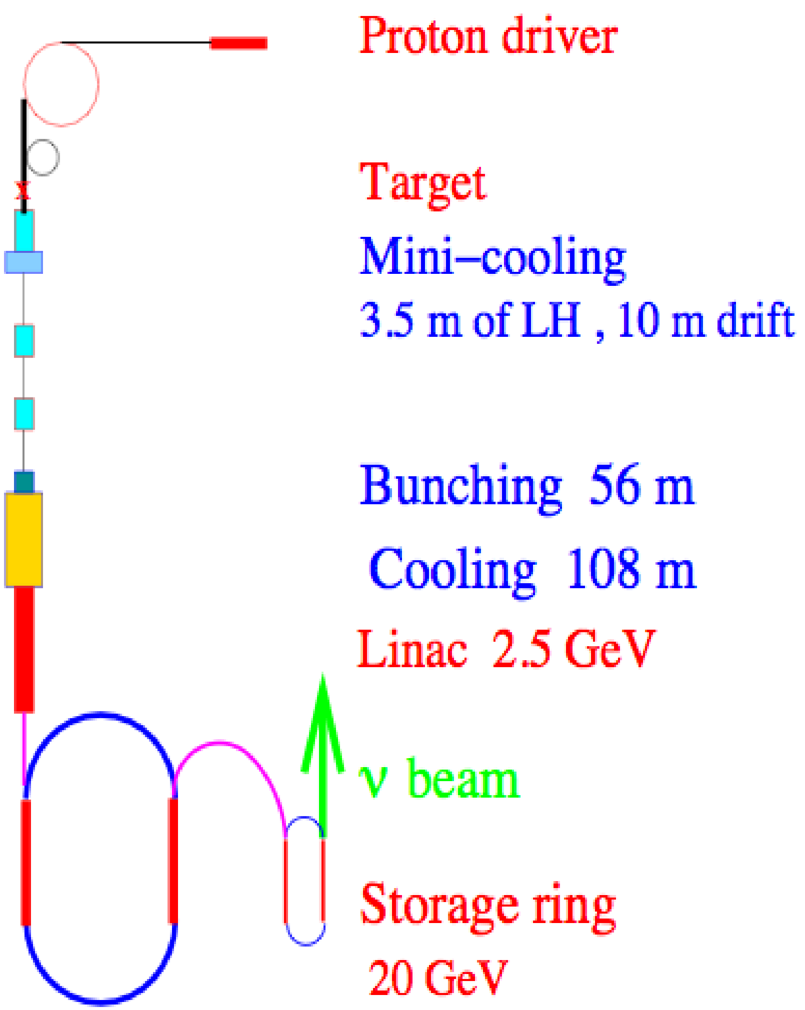

M. Bishai, LBNE

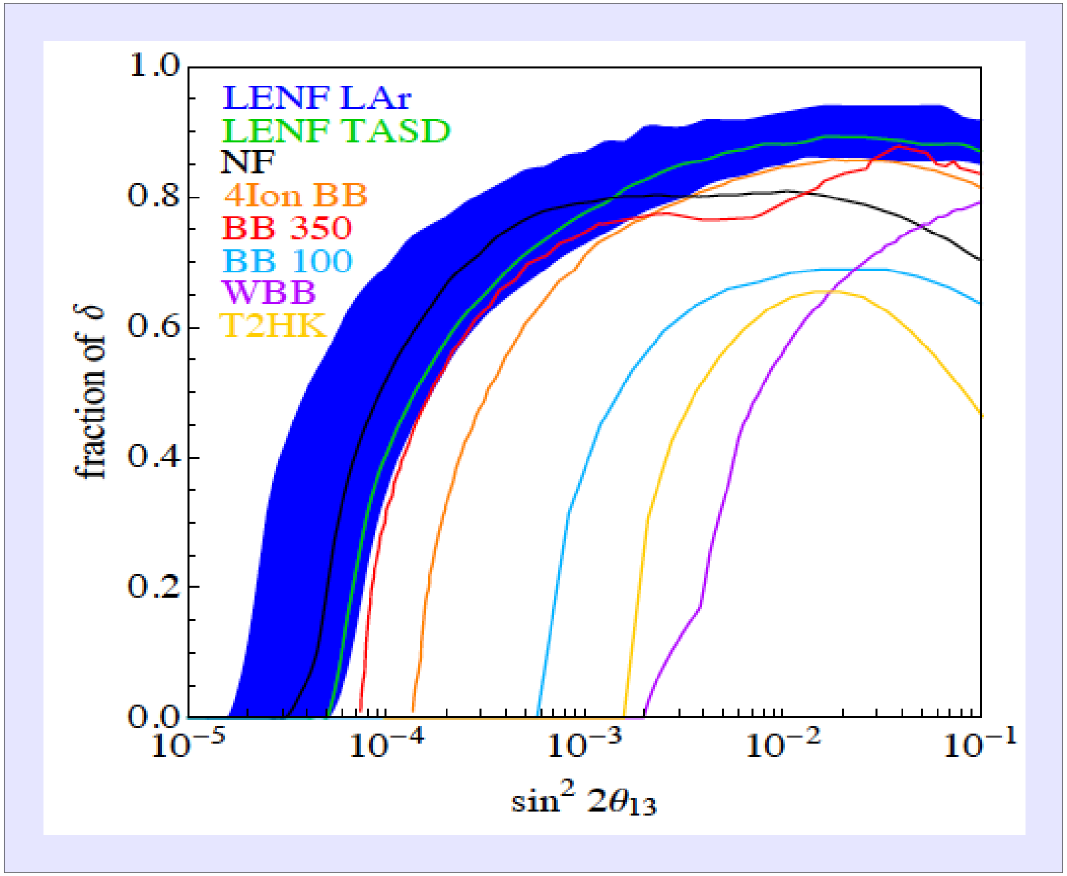
# NOvA

Goals: theta13 and CPV

Due to the long baseline, it has some sensitivity to matter effects.

# Neutrino factory




Sensitivity of a future low energy neutrino factory. [Fernandez-Martinez, Li, Mena, Pascoli]

The physics reach of the facilities is actively studied at present in order to shape the future experimental neutrino program.

**Why studying neutrinos?**

Neutrino Physics provides information on the fundamental laws of Nature and on the evolution of the Universe.

**Open window on the Physics beyond the SM at scales, possibly not otherwise reachable.**

**Neutrinos are messengers from the Early Universe and from Extreme Astrophysical Environments.**

## Experiments

- Neutrinoless double beta decay
- Long baseline oscillations
- Direct mass searches
- Other oscillation experiments

## Phenomenology

## Astroparticles

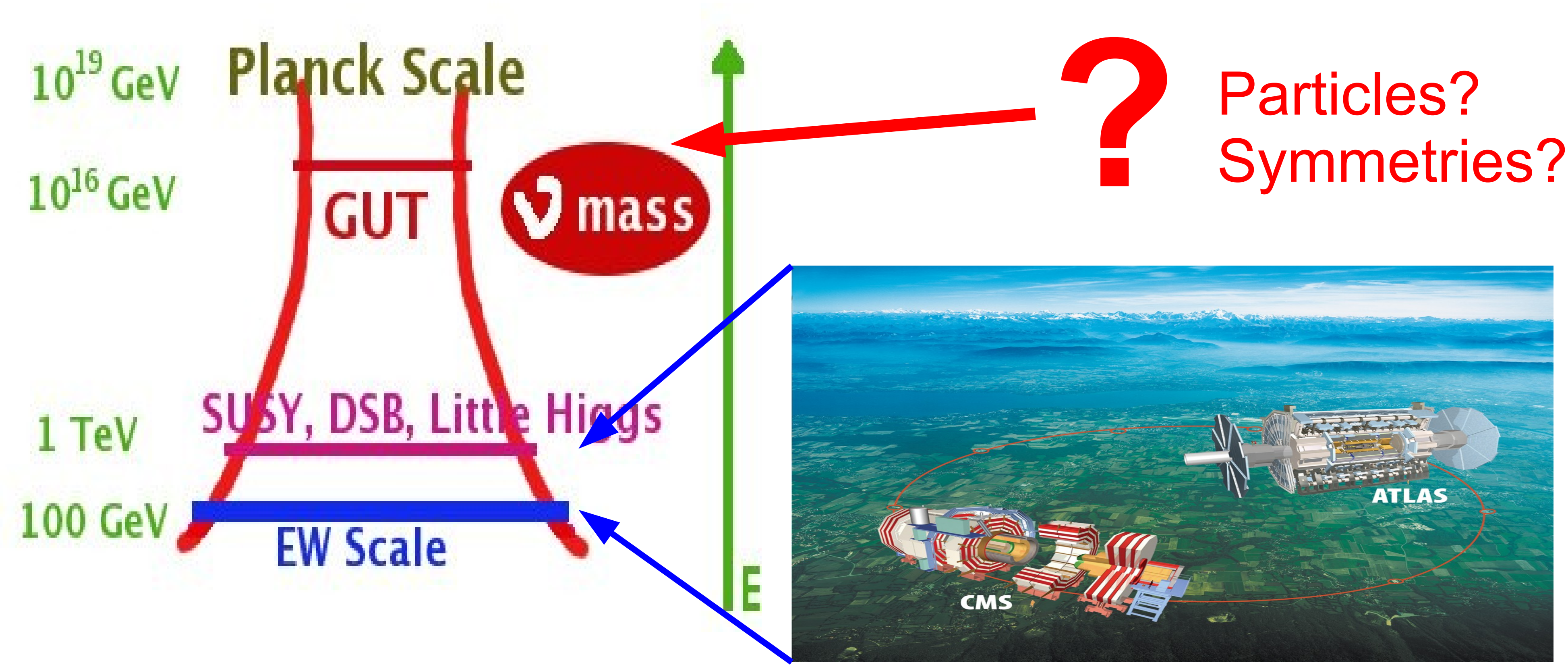
- Constrain nu properties
- Study evolution of Universe

## Theory

- Origin of neutrino masses BSM
- Flavour problem

# **Open window** on Physics beyond the SM: 1.

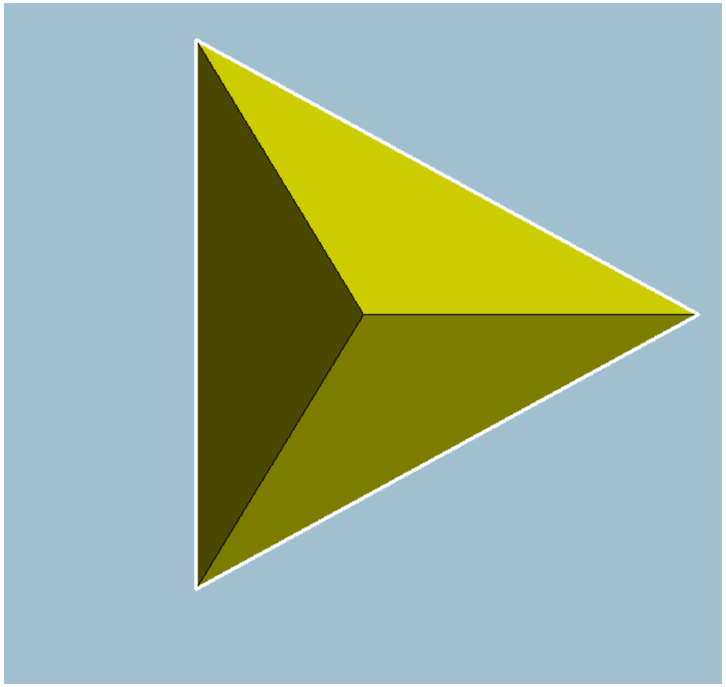
LHC experiments will search for the Higgs boson and for new physics at the TeV scale. What is beyond that?




Neutrinos are much lighter than the other particles: maybe their mass has a different origin. Neutrino physics gives a new perspective on physics BSM.

# **Open window** on Physics beyond the SM: 2.

Mixing in the leptonic sector is very different from the quark one: angles are large and there can be new sources of CP-violation.
Different perspective on the flavour problem.



Why three generations?

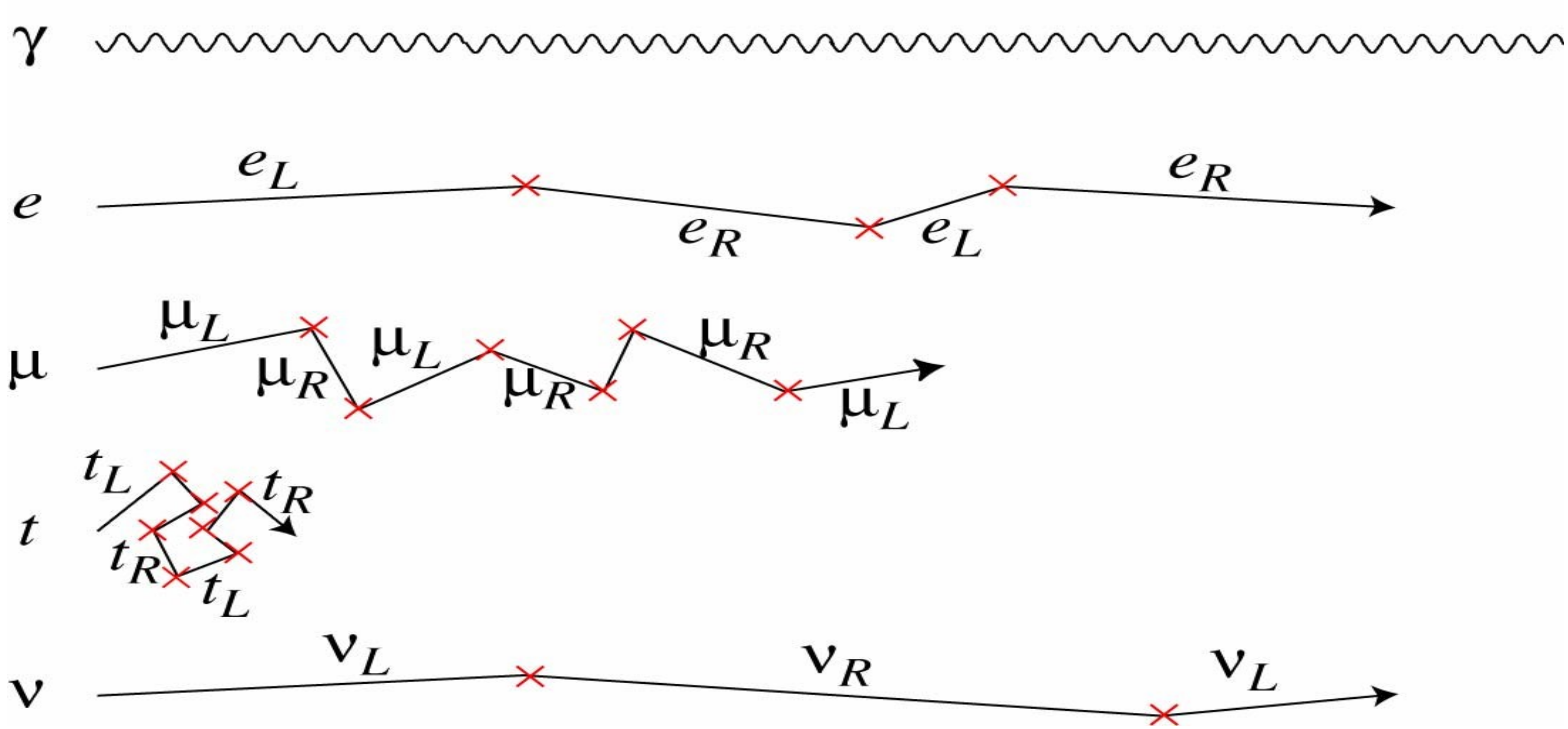
Why massive and flavour particles are not the same?

Why the angles have the values measured?

What is the origin of CPV?

The information from the leptonic sector (neutrinos) is **complementary** with the one which comes from flavour physics experiments and from colliders (Tevatron, LHC).

Neutrino masses in the sub-eV range cannot be explained naturally within the SM. If neutrinos had the same interactions with the Higgs as the top quark, they would be **100000000000** times heavier!

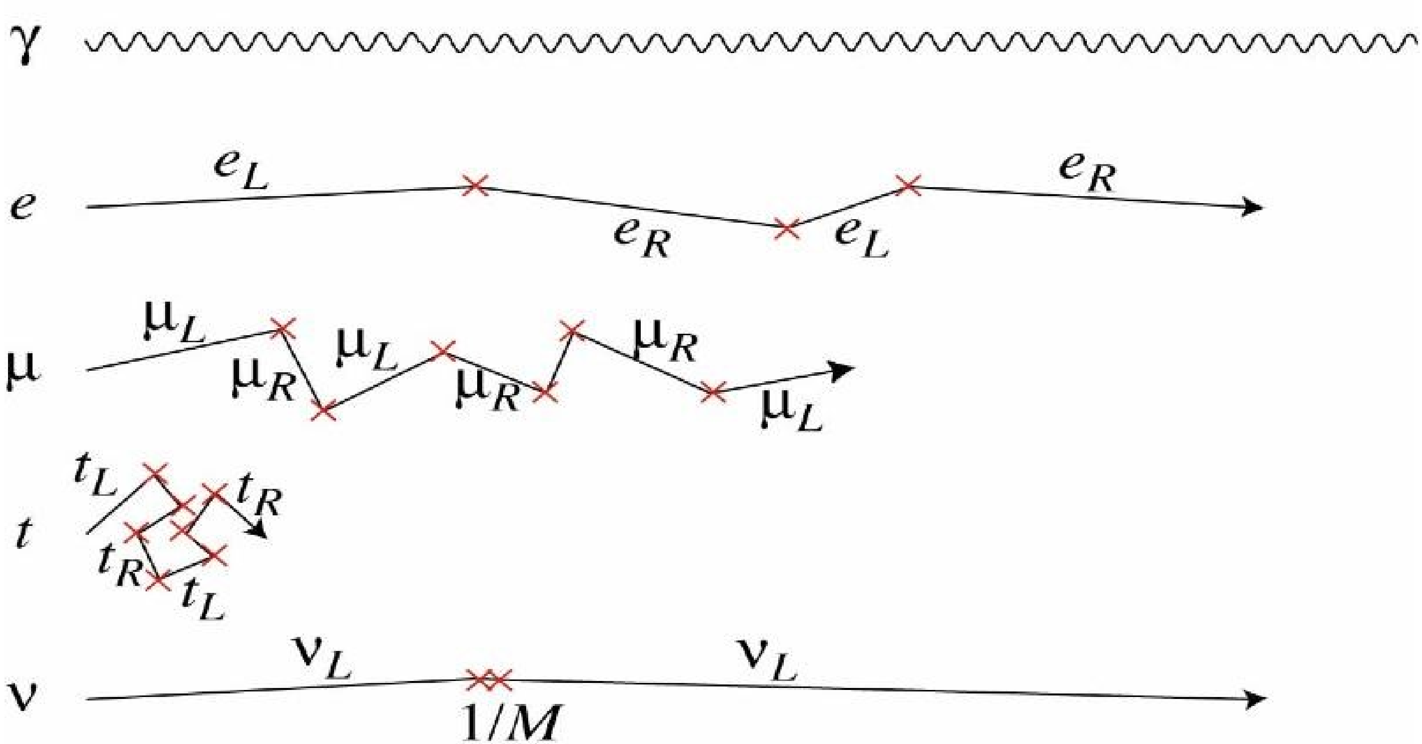



Thanks to
H. Murayama

$$y_\nu = \frac{m_\nu}{v} = \frac{0.1\,\mathrm{eV}}{250\,\mathrm{GeV}} = 4 \times 10^{-13}$$

Many theorists consider this explanation of neutrino masses unnatural.

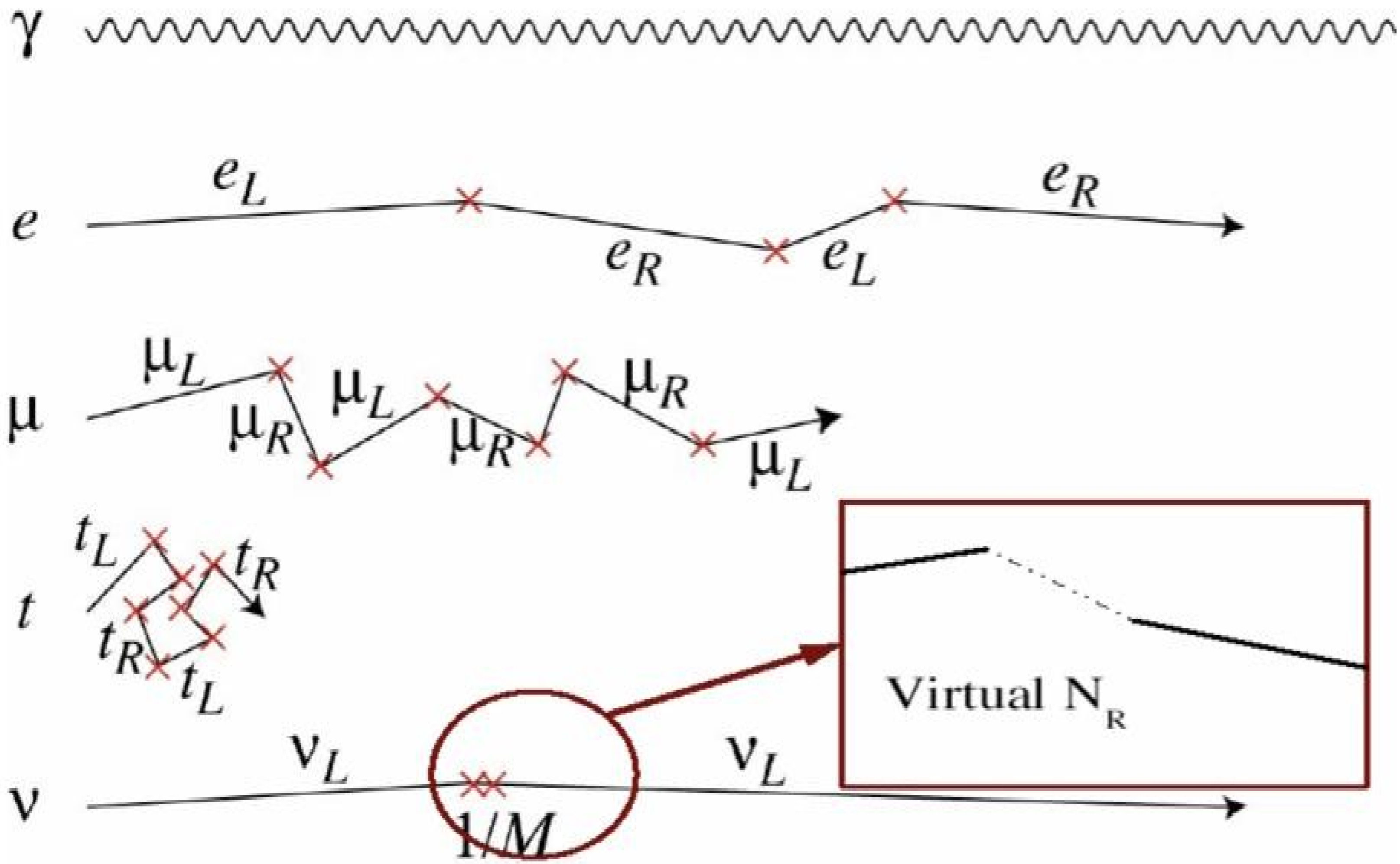
If neutrino are Majorana particles (neutrinos and antineutrinos are indistinguishable), a different type of neutrino mass can be generated (**Majorana mass**):




Thanks to
H. Murayama

$$-\mathcal{L} = \lambda \frac{\nu_L H \; \nu_L H}{M} = \frac{\lambda v^2}{M} \nu_L^T C \nu_L$$

The Majorana mass term can arise as the **low energy realisation of a higher energy theory**.

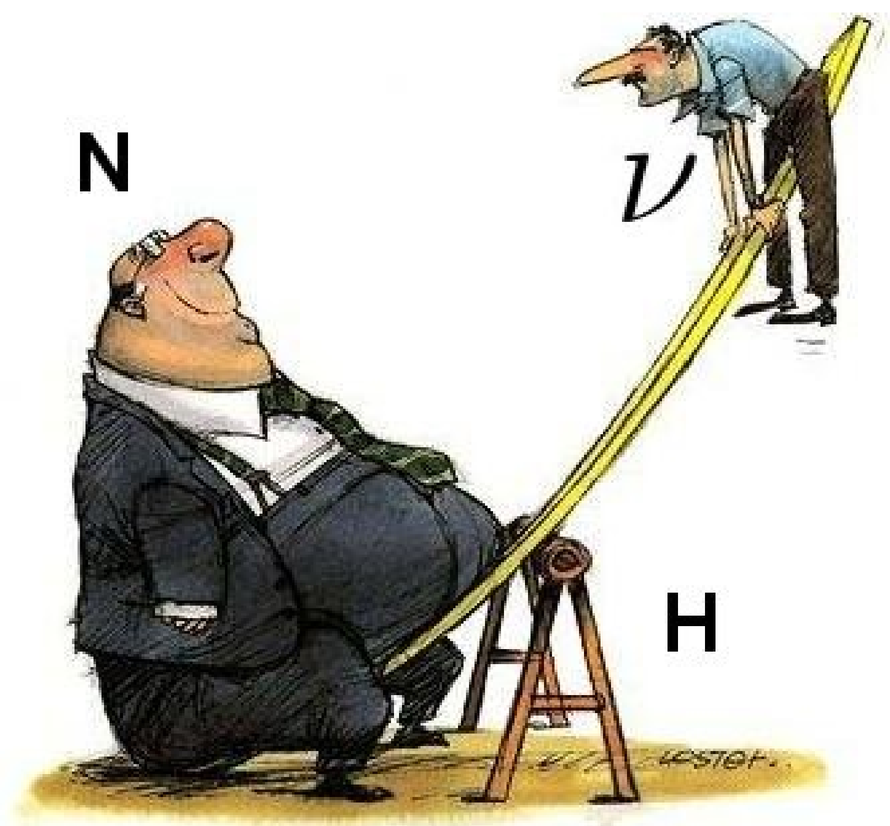



Thanks to
H. Murayama

$$m_\nu = \frac{\lambda^2 v^2}{M} \rightarrow M \sim 10^{14}\ \mathrm{GeV}$$

# The see saw mechanism

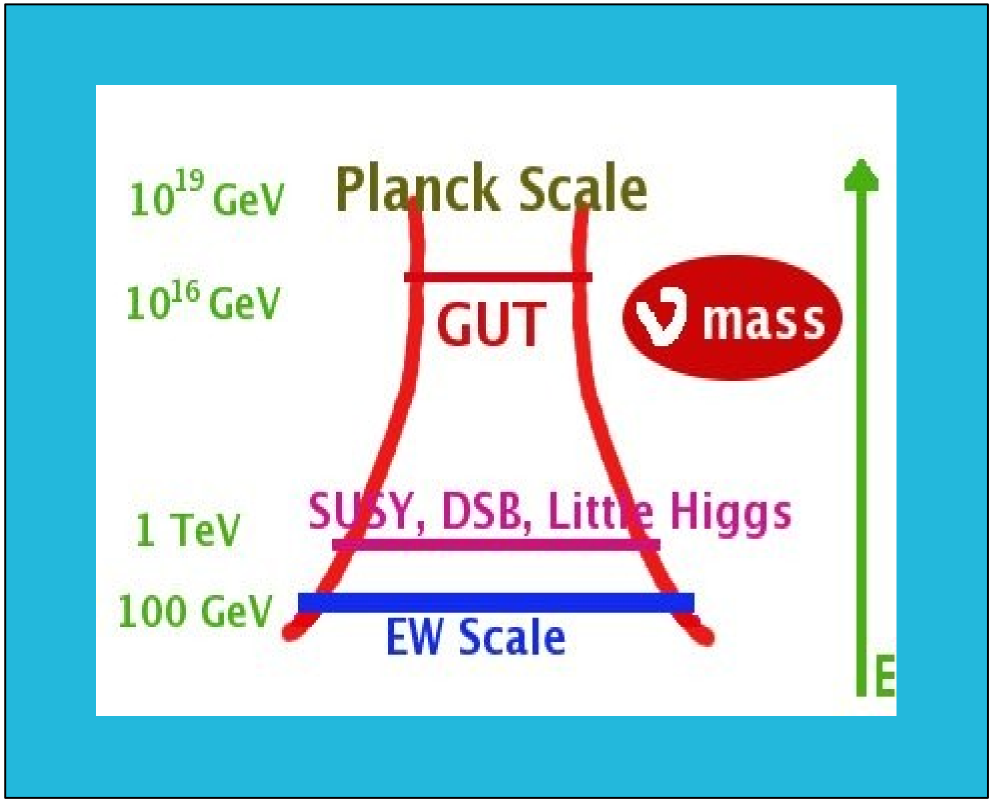
In the **see-saw mechanism**, neutrinos acquire a very small mass due to their interactions. Minkowski; Yanagida; Gell-Mann, Ramond, Slansky.

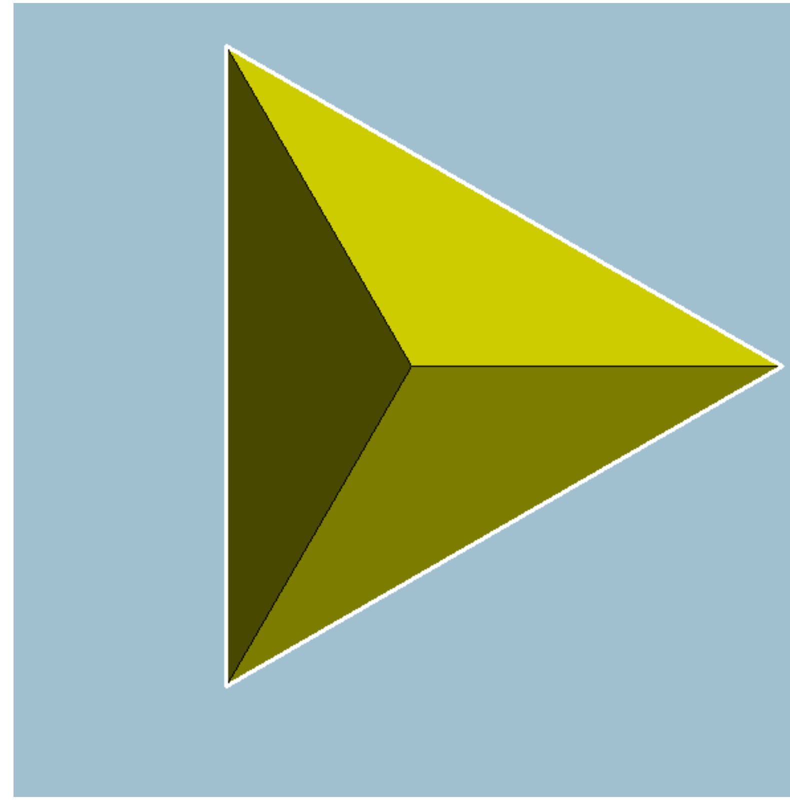



- Introduce a right handed neutrino **N**
- Couple it to the Higgs and left handed neutrinos

$$m_{light} \simeq \frac{m_D^2}{M_R} \sim \frac{100\ \mathrm{GeV}^2}{10^{14}\ \mathrm{GeV}} \sim 0.1\ \mathrm{eV}$$

Other possibilities: Neutrinos masses might be due to new physics at a lower scale, as low as the electroweak scale or below, testable at the LHC.



Understanding the origin of neutrino masses will shed **light** on the physics at **energy scales** which might not be tested directly in experiments and neutrino mixing offers a different perspective on the **problem of flavour**.

It is critical to combine this information with collider data from Tevatron and LHC, LFV searches, flavour physics.

# Neutrinos are messengers from the Universe

Supernovae

Dark Matter annihilations

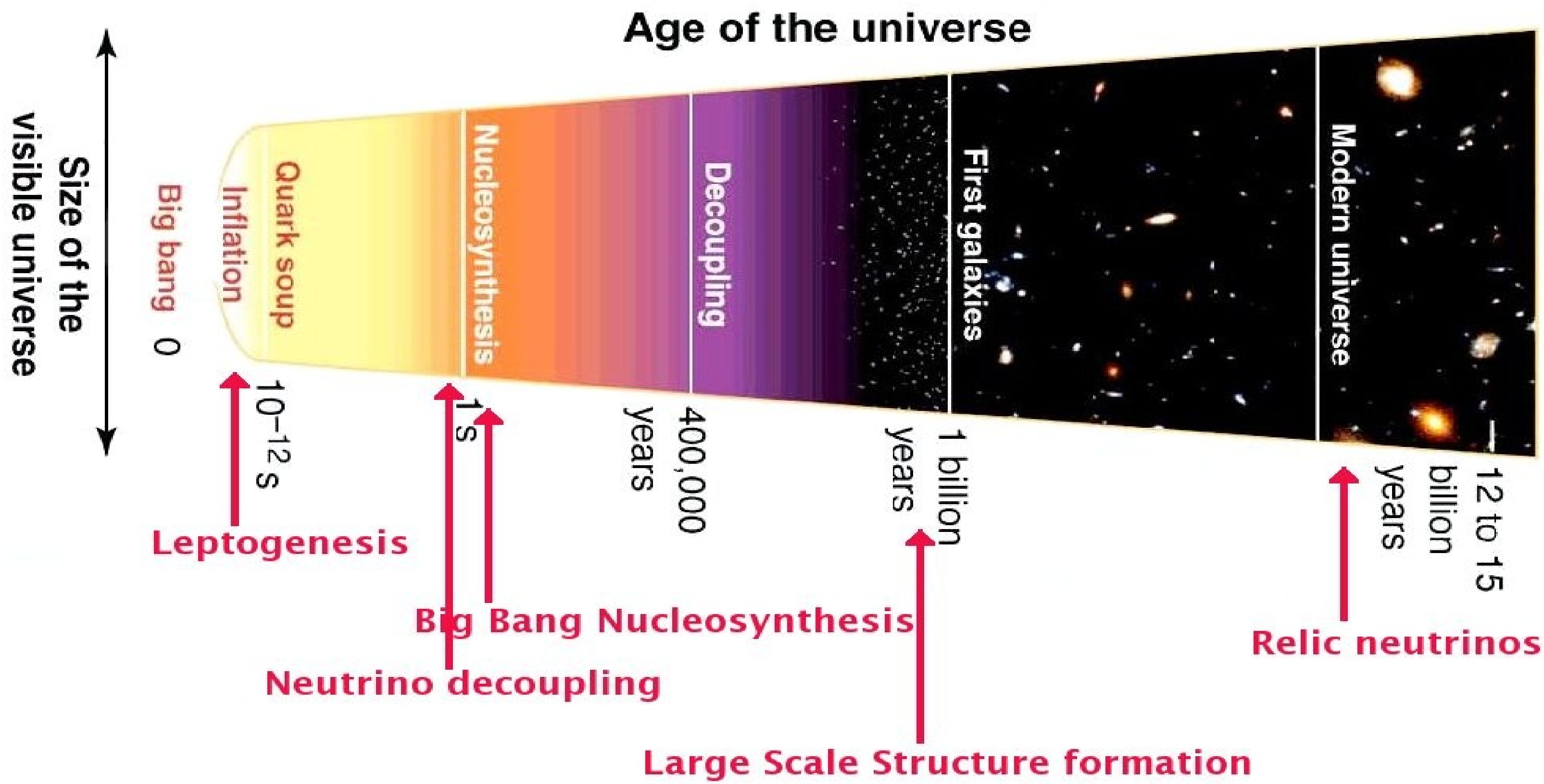
Leptogenesis

Relic neutrinos

Sterile Neutrinos as Dark Matter

Big Bang Nucleosynthesis

HDM and structure formation

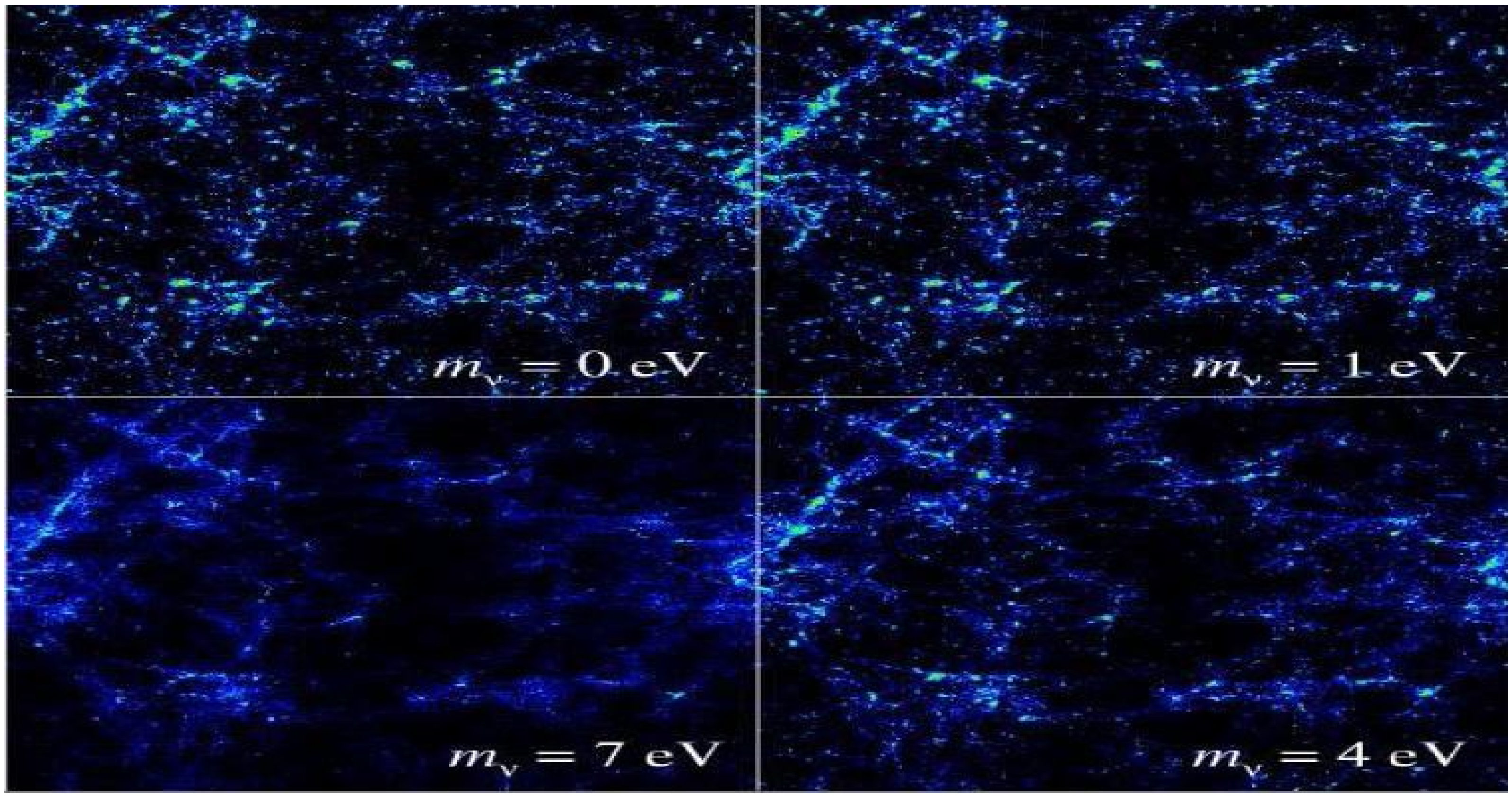



How many **relic neutrinos** are in a **cup of tea**?

5600!

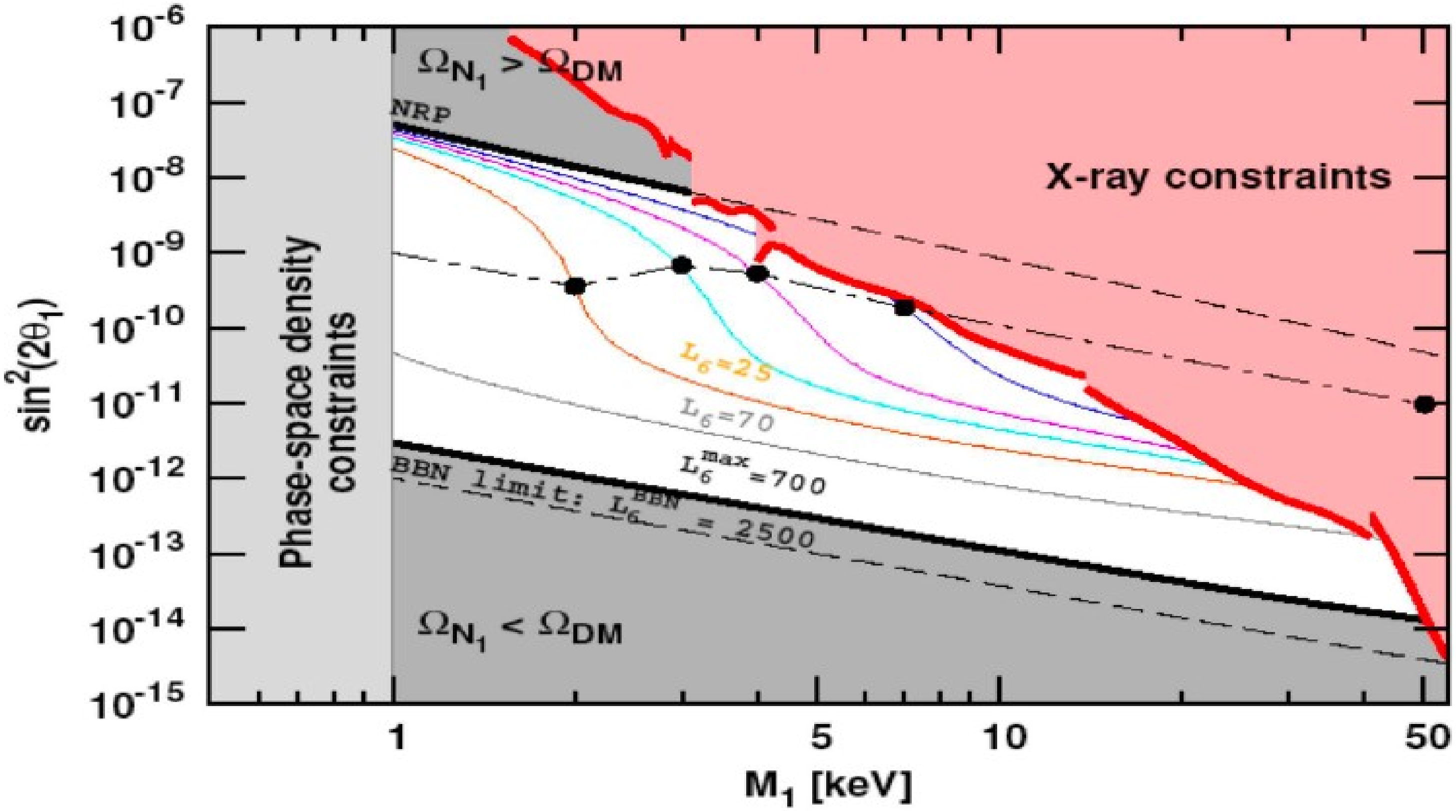
# Neutrinos and dark matter

Neutrinos constitute a **hot dark matter** component and affect the formation of clusters of galaxies.




**Neutrinos are too hot** for being trapped in the gravitational wells in the Early Universe (**free streaming**) and move freely, smoothing out the structures (galaxies) at small (cosmological) distances.

• From cosmological observations, one can deduce **bounds on neutrino masses: m< 0.2-0.5 eV**, to be compared with experimental searches.




Boyarsky et al, 2010

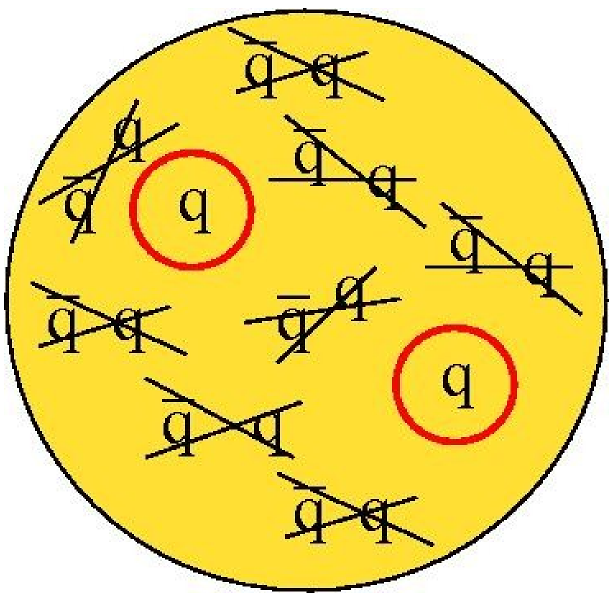
• **Mostly-sterile neutrinos** (massive neutrinos which have interaction with SM particles much weaker than the standard neutrinos), if existing, would have been produced in the EU and **can constitute all or part of the DM**.

# Leptogenesis and the Baryon Asymmetry

**10000000001 quarks**

In the Early Universe

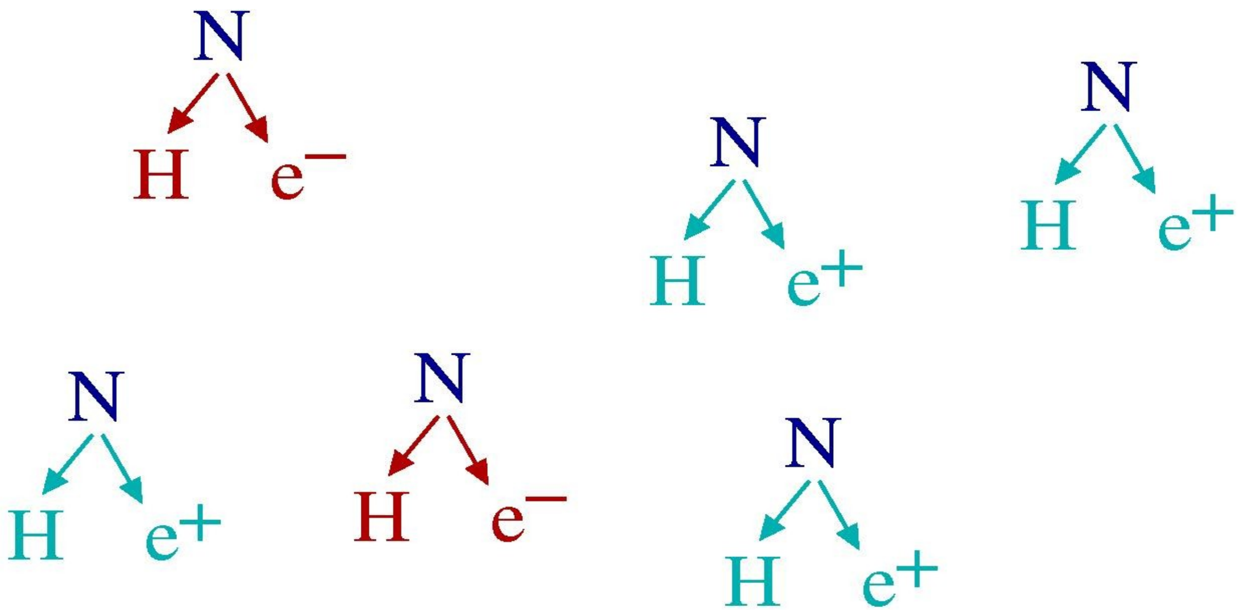
**10000000000 antiquarks**



As the temperature drops, only quarks are left:

$$Y_B = \frac{n_B}{n_\gamma} = (6.0 \pm 0.2) \times 10^{-10}$$

The excess of quarks can be explained by **Leptogenesis** (Fukugita, Yanagida):
the N responsible for neutrino masses generate a lepton asymmetry.




Excess of $e^{+} \longrightarrow$ excess of $q$ over $\bar{q}$

This requires **L violation, CP-violation** and **non-equilibrium** (expansion of the EU).

The lepton asymmetry is then converted into the observed baryon asymmetry.

The **see-saw mechanism** (type I) might be responsible both for **neutrino masses** and for the **baryon asymmetry**.

Is there a **connection** between the two**?** i.e. if I measure CP at low energy can we be sure that the baryon asymmetry comes from leptogenesis?

• In general, there are more parameters at high energy (where leptogenesis happens) w.r.t. the ones we can measure in experiments at low energy.

• The number of parameters is typically reduced in **models of flavour** (symmetries, texture zeros) and a **connection** can be present.

•Due to **flavour effects**, if we **observe CPV at low energy** we know that generically a **baryon asymmetry** was generated (although we cannot predict its magnitude).

• **Observing L violation and CPV** would constitute a **strong hint in favour of leptogenesis as the origin of the baryon asymmetry**.

# The **Diamond Era** of Neutrinos:

## much harder but much brighter than before.

Following the recent discoveries, an exciting experimental program is planned for the future to determine neutrino masses and mixing parameters.

This information is **complementary** to the one from flavour physics experiments and from colliders (Tevatron, LHC).

**Our work will help in opening a new window on the fundamental laws of nature, its fundamental constituents and the evolution of the Universe.**